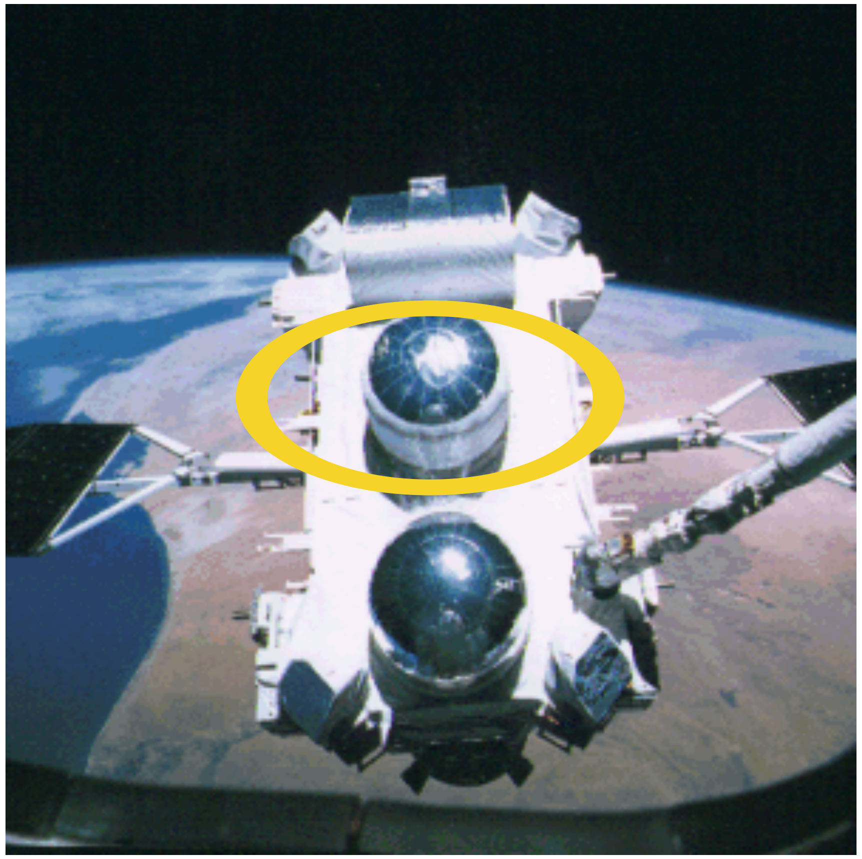
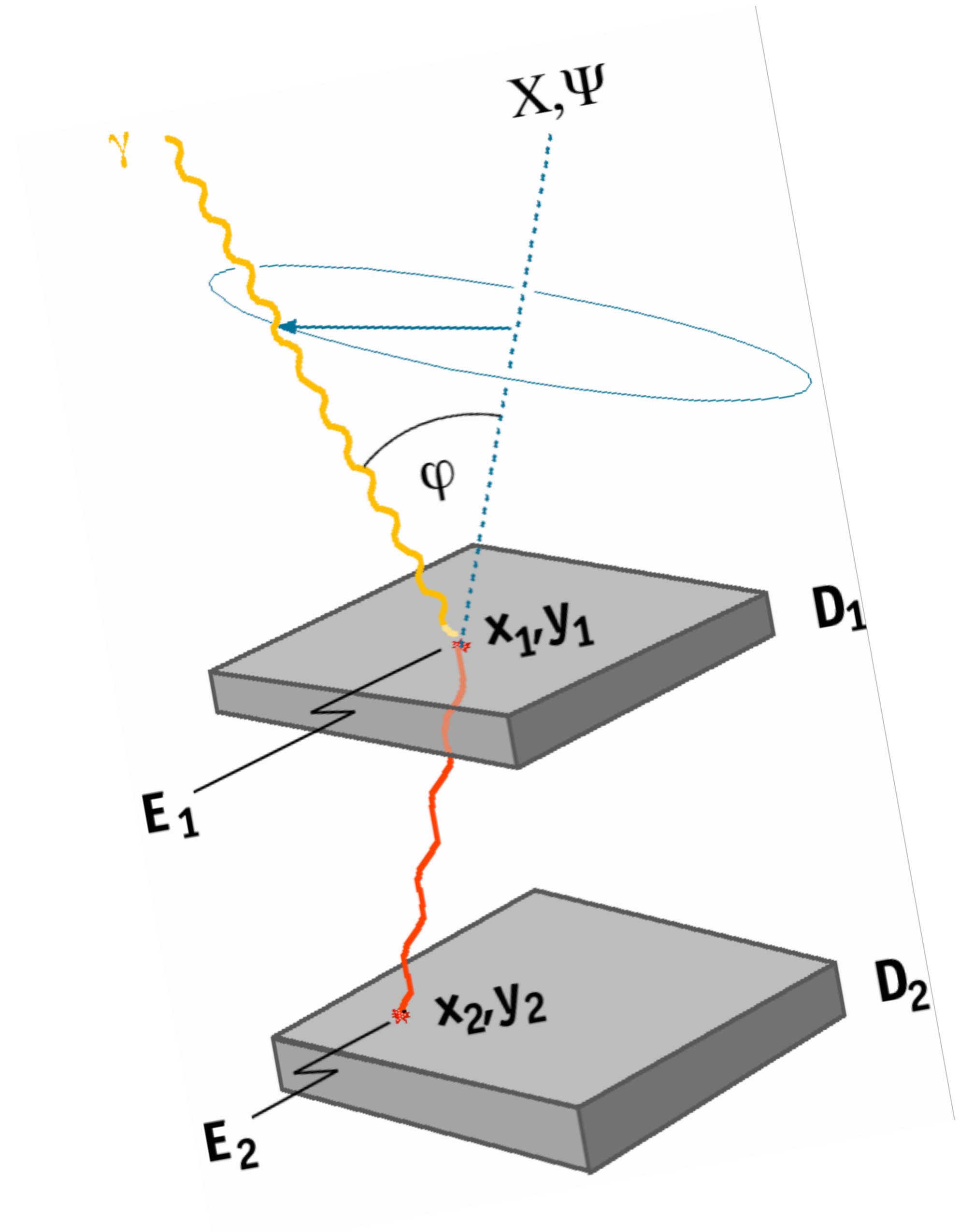
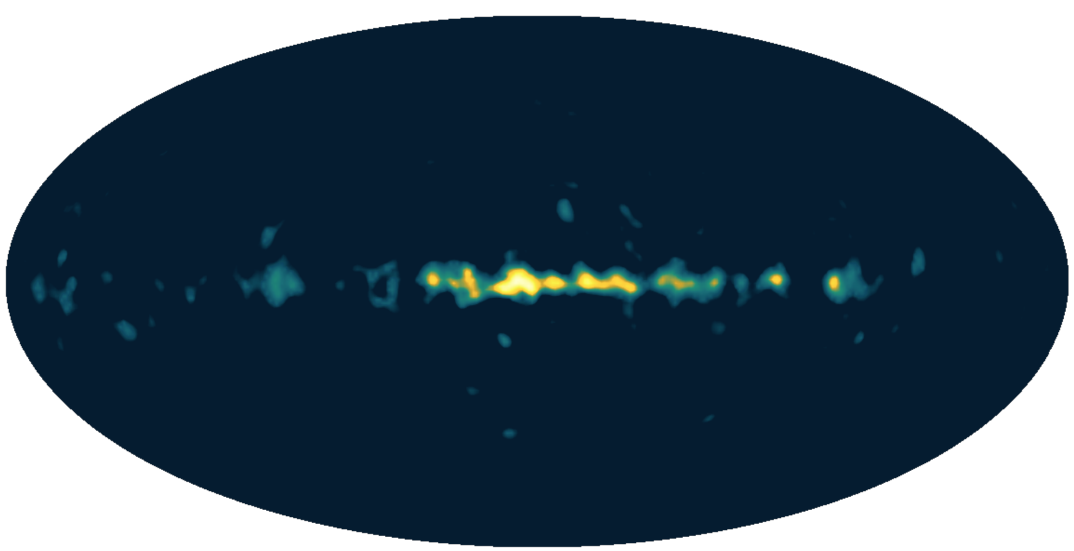


Compton telescopes: Design considerations, etc



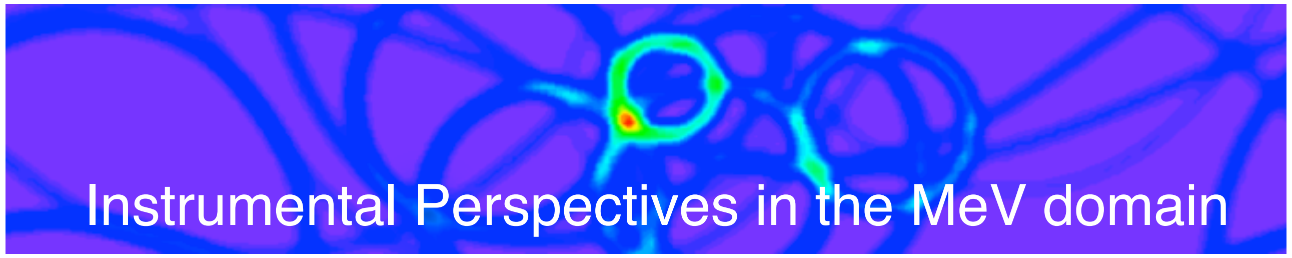
J. Eric Grove

Naval Research Laboratory



first ^{26}Al all-sky map

Slides borrowed from … etc.



Instrument Options in the MeV range

What made progress so slow ?

Recent R&D projects towards a future MeV mission

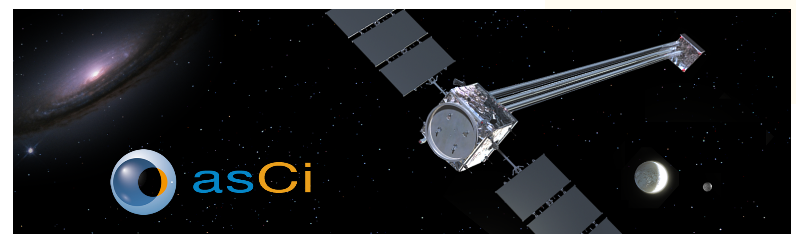
Peter von Ballmoos, IRAP Toulouse

GAMMA CUBE

(LE – GLAST)

A scintillation tracker

R. Chipaux, P. Laurent, F. Lebrun, R. Terrier



all sky Compton imager

design considerations for Compton Telescopes
the asCi choice - detector and mission concept
performance estimates
one more thing

Peter von Ballmoos, IRAP Toulouse

NCT

The Nuclear Compton Telescope

A balloon-borne gamma-ray spectrometer, polarimeter, and imager

Steve Boggs

for the NCT collaboration

Thick Silicon Compton Imager for ACT

Bernard Phlips
Jim Kurfess
Eric Wulf
Elena Novikova
Neil Johnson

18 August 2005

18 August 2005 ACT Team Meeting

Simulations of a Si-based Advanced Compton Telescope (ACT)

Elena I. Novikova[1], Eric A. Wulf[1], Bernard F. Phlips[1], James D. Kurfess[1], Andreas Zoglauer[2], Georg Weidenspointner[3], R.Marc Kippen[4]

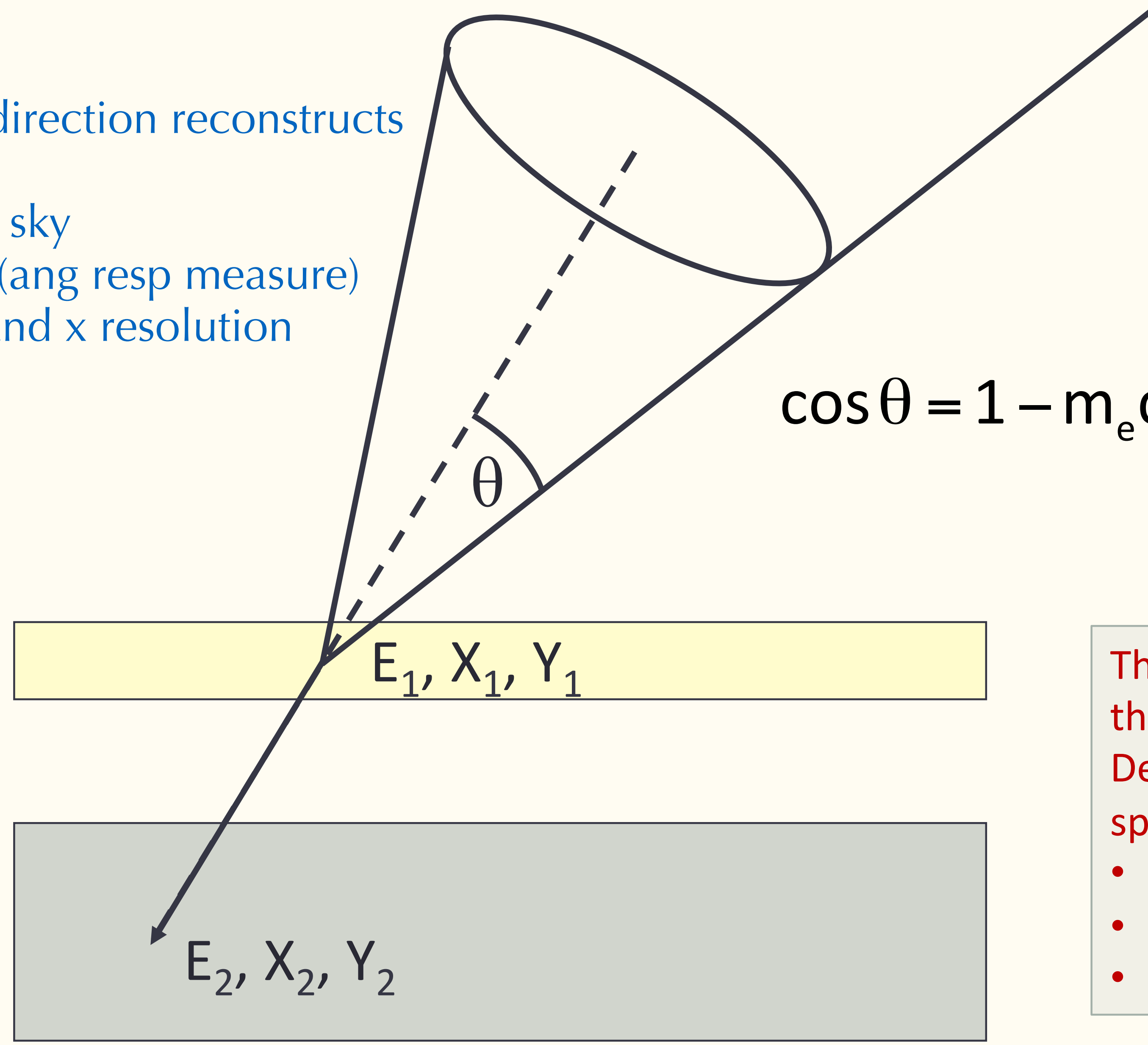
[1]NRL, Washington, DC, USA
[2]UC Berkeley, CA, USA
[3]CESR, Toulouse, France
[4]LANL, Los Alamos, NM, USA

October 26, 2005 IEEE NSS N19-5 Puerto Rico 1

Principles

Compton telescope principle

- Incident g-ray direction reconstructs to a cone
  - Annulus on sky
- Width of cone (ang resp measure) depends on E and x resolution



D1 scatterer

D2 absorber

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

The angular resolution depends on the spectral performance. Detectors must have good spectrometry performances, e.g.:

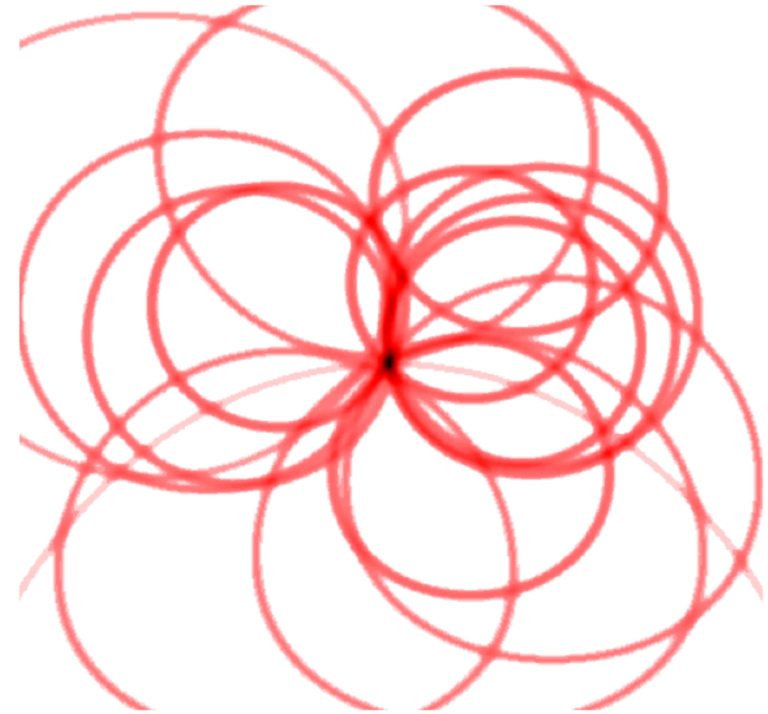
- Ge
- Si
- $LaBr_3$

Must have good dE and good dx
Must fully absorb in D2

from Lebrun, Nov 2013, Gamma Cube

Compton imaging

- Image
  - Each photon = ring
  - Intersection of many rings
- Issue
  - Source confusion
  - Rejection of sky background
  - Complicated PSF

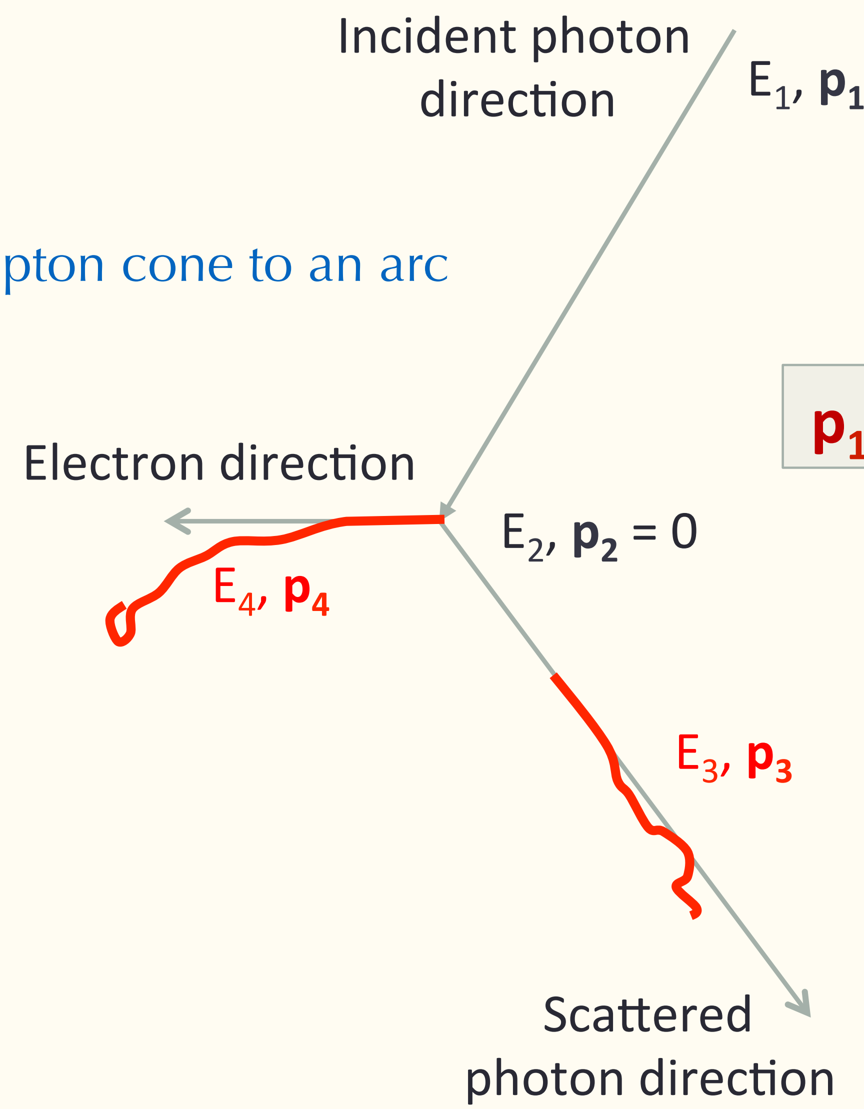


- The origin of a single not-tracked event can be restricted to the so called “event circle”.
- The photon originated at the point of all overlap.

- Mitigation
  - Best possible E and position resolution
    - Keep them well matched
  - Get more information about the scatter in D1: track the recoil electron

Electron tracking

Measuring the recoil-electron track



– Reduces Compton cone to an arc

Measuring the electron track (and its propagation direction) allows for an almost complete interaction reconstruction

$$\mathbf{p_1} = [(E_4^2 + 2\,E_4E_2)^{1/2}\,\mathbf{p_4} + E_3\,\mathbf{p_3}] / (E_4 + E_3)$$

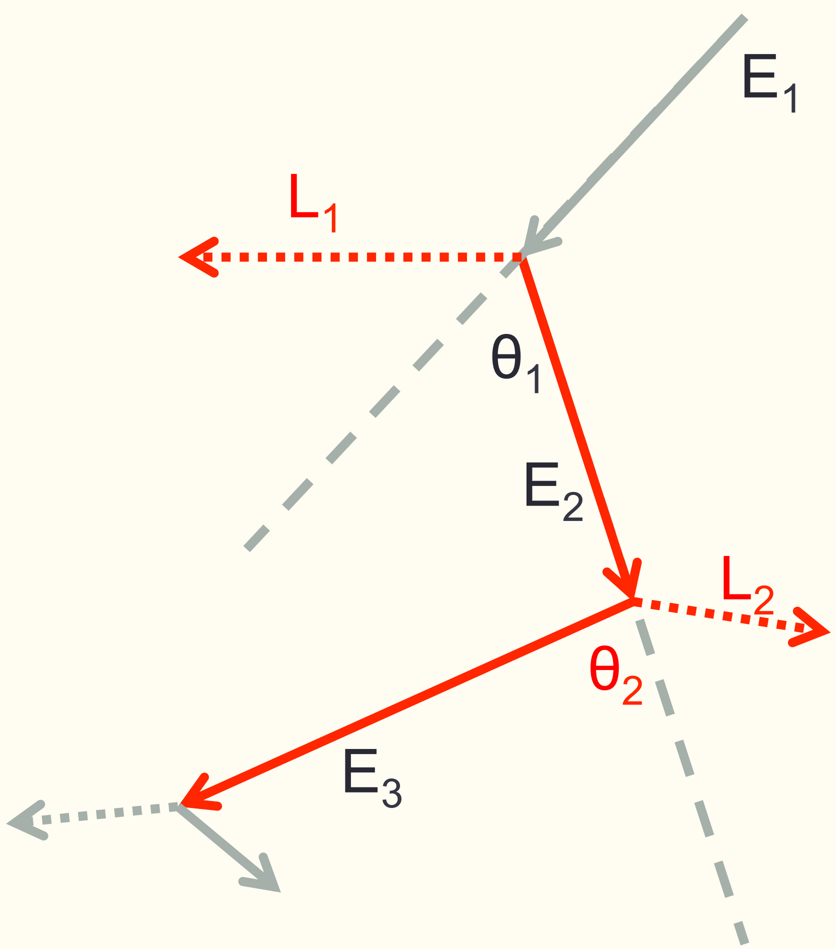
$E_2 \neq 0 \rightarrow$ “Doppler broadening”

Momentum of target electron matters
Most important below 1 MeV
Low-Z scatterer gives measurably better resolution

from Lebrun, Nov 2013, Gamma Cube

Multiple-Compton

First 3 interactions



E_1=L1+1/2 (L2+√2&L22+ 4 mec2 L2/1−cosθ2)

- Can measure incident E without fully absorbing scattered gamma
- Thick, high-Z target isn't required

No need for full absorption !

Kurfess et al. 2003, US patent

from Lebrun, Nov 2013, Gamma Cube

Multiple-Compton technique

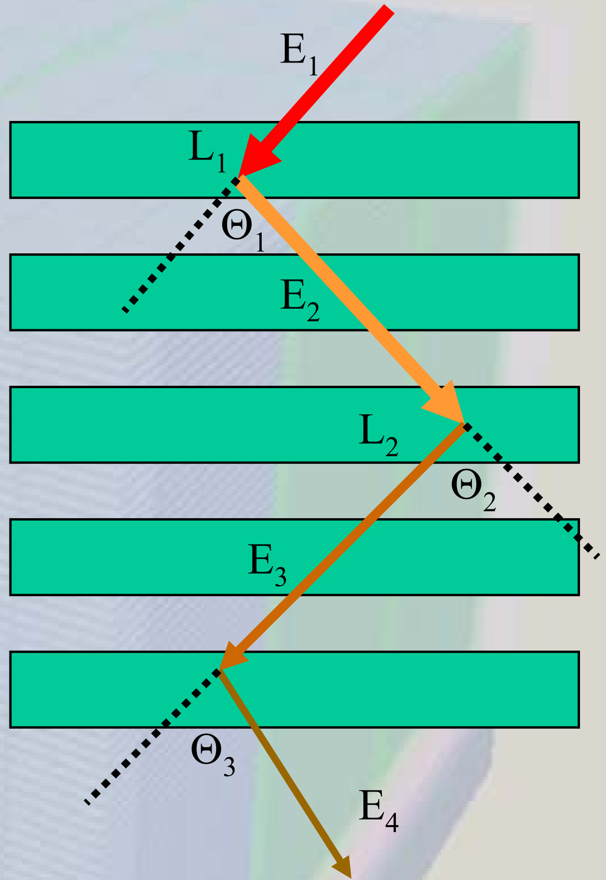
Three Gamma Interaction Technique

Θ_2 is computed from geometry;

$$E_1 = L_1 + \frac{L_2 + \left[L_2^2 + \frac{4 m_e c^2 L_2}{1 - \cos\Theta_2} \right]^{\frac{1}{2}}}{2}$$

above is derived from:

$$\begin{cases} \cos\Theta_2 = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2} \right) \\ L_2 = E_2 - E_3 \end{cases}$$



- **Unknown source: 3 interactions required to determine energy, *E_1***
- **Known source: 2 interactions required to determine energy, *E_1***
- **Does *not* require total energy absorption**
- **Efficient Compton telescope, even if using *silicon* detectors**
- **Ordering algorithm is essential**

See N1-1: Wulf et al. for prototype results

Multiple-Compton technique

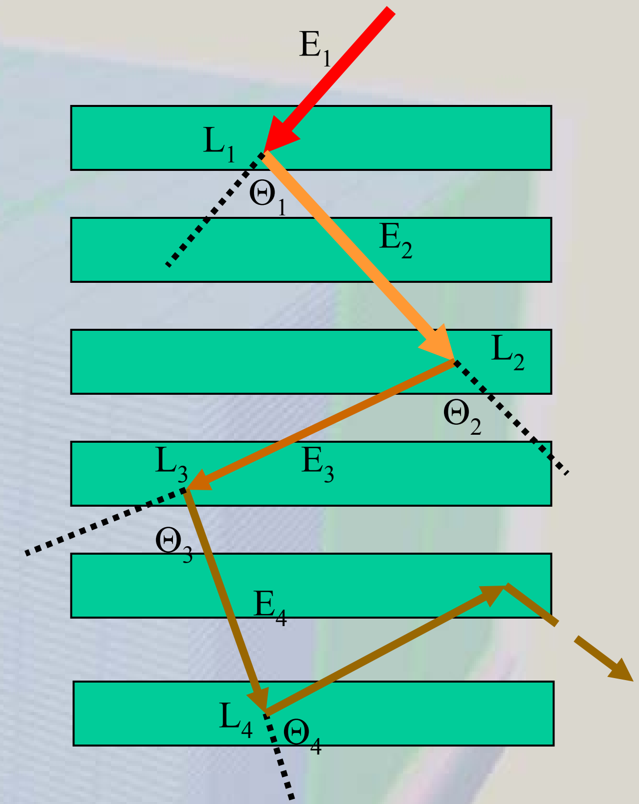
- Warning: order of scatters is essential, and number of scatters can be large

Multiple Estimates of Incident Gamma Ray Energy

$$E_1 = L_1 + \frac{L_2 + \left[L_2^2 + \frac{4 m_e c^2 L_2}{1-\cos\Theta_2} \right]^{\frac{1}{2}}}{2} \; ;$$

$$E_1 = L_1 + L_2 + \frac{L_3 + \left[L_3^2 + \frac{4 m_e c^2 L_3}{1-\cos\Theta_3} \right]^{\frac{1}{2}}}{2}$$

$$E_1 = L_1 + L_2 + L_3 \frac{L_4 + \left[L_4^2 + \frac{4 m_e c^2 L_4}{1-\cos\Theta_4} \right]^{\frac{1}{2}}}{2}$$



- **Ordering algorithm is essential**
- **N hits result in N! possible sequences**
- **N interactions provide N-2 estimates of E_1**
- **Sequence with the most consistent estimates of E_1 is accepted**
- **Currently accept only events with 4 to 8 hits, and fully absorbed events with 3 hits**
- **In the future: check Klein-Nishina and absorption probabilities; electron tracking**

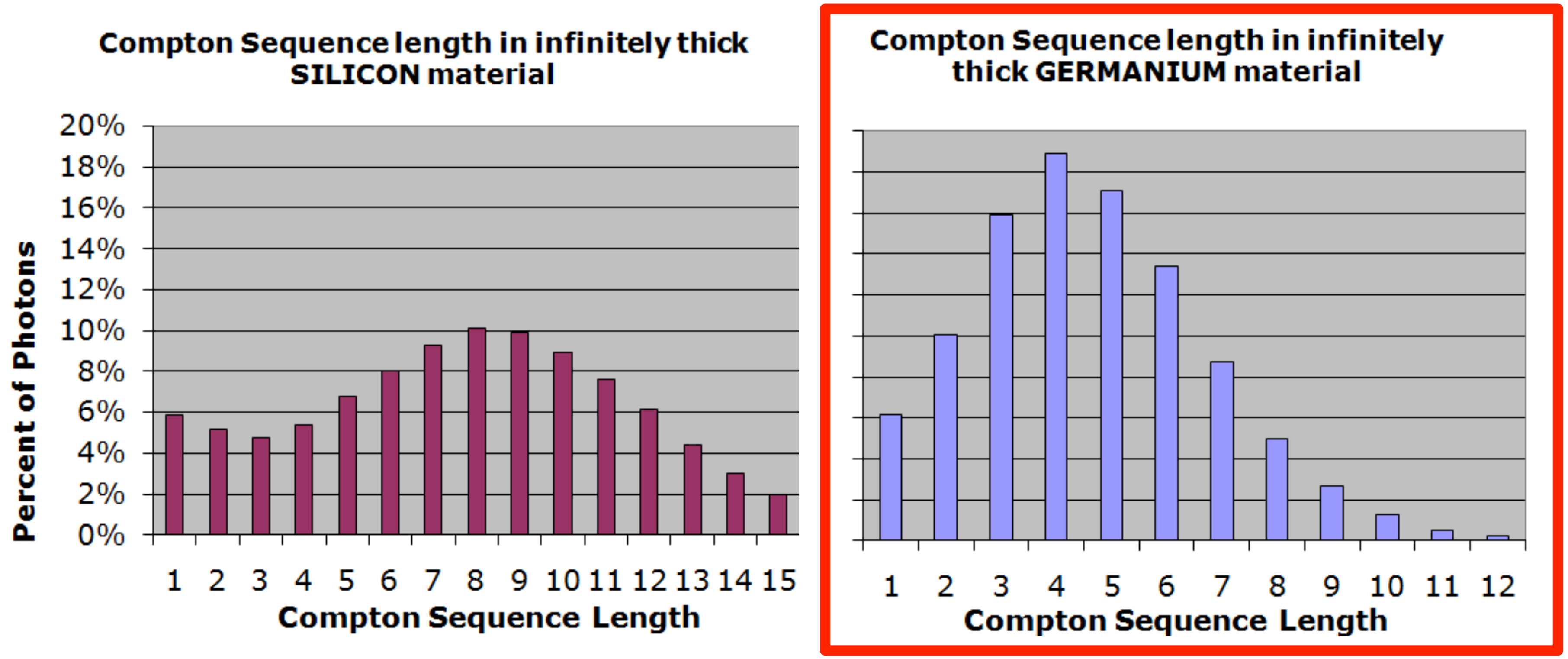
October 26, 2005 IEEE NSS N19-5 Puerto Rico 8

Novikova (NRL) et al. 2005 – Si ACT

How common are multiple Comptons?

- Very, so don't throw them out
  - Maybe Si-only Compton telescope isn't optimal, but needs higher Z somewhere

asCi design considerations - material



Ge : 4±2 interactions needed to transform full energy (75% of photons)
Si : 8+3-2 interactions needed to transform full energy (75% of photons)

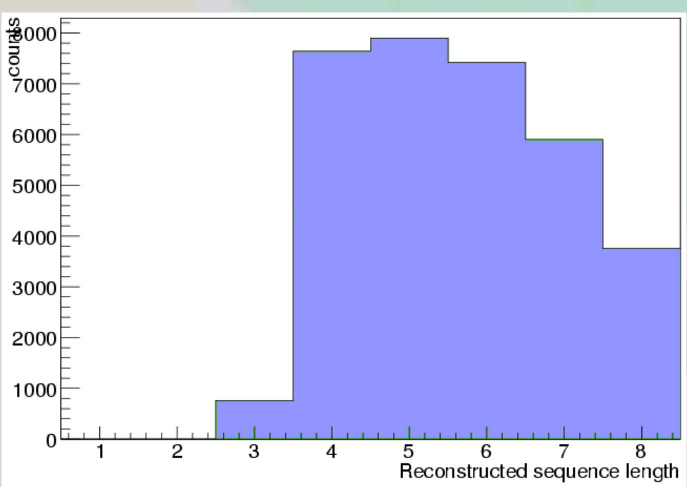
Ge : provides sufficient number of interactions (algorithms require ≥ 2) while providing enough stopping power to prevent too many interactions (makes reconstruction impossible, since they increase with *n*!) and increase the chance of the full photon energy being deposited.

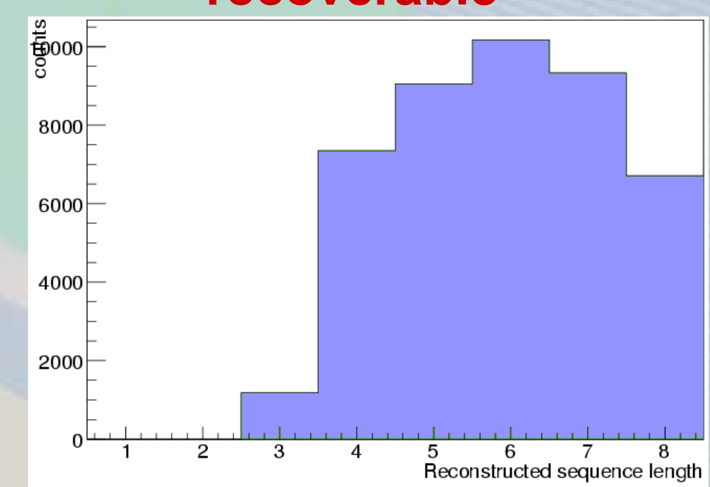
from von Ballmoos, Nov 2013, Instrumental Perspectives …

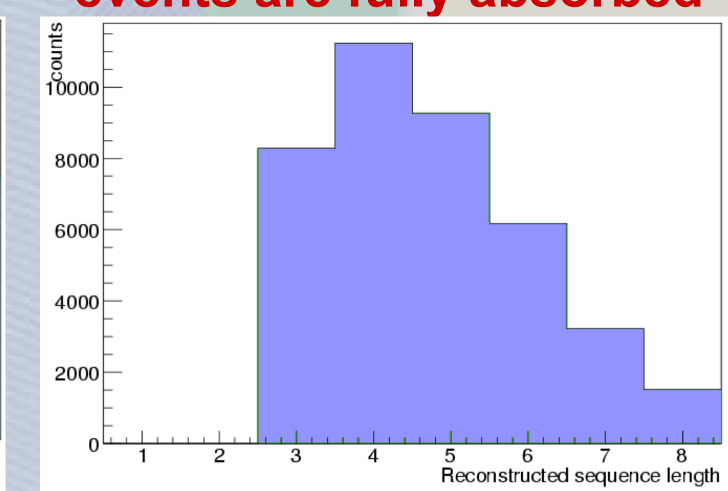
Mass model modifications

Compton sequence length for: Horizon cut 92.5^0; E = 847 +/- 22.75 keV; 1 mil events

Main Model	Thicker Si (Wafer Bonding*)	Si interleaved with CZT
64 x 3mm Si	25 x 7.5mm Si	(5mm CZT + 12 x 3mm Si) x 4
Baseline	Less dead material: longer sequences are recoverable	High-Z material interleaved: no need for longer sequences, because more events are fully absorbed







Main Model	Thicker Si	Si interleaved with CZT
Eff. Area 860 cm^2	Eff. Area 1266 cm^2	Eff. Area 1073 cm^2
FWHM Ang.Res: 1.44^0	FWHM Ang.Res: 1.9^0	FWHM Ang.Res: 1.78^0

*see N35-62: Phlips et al. for wafer bonding

Novikova (NRL) et al. 2005 – Si ACT

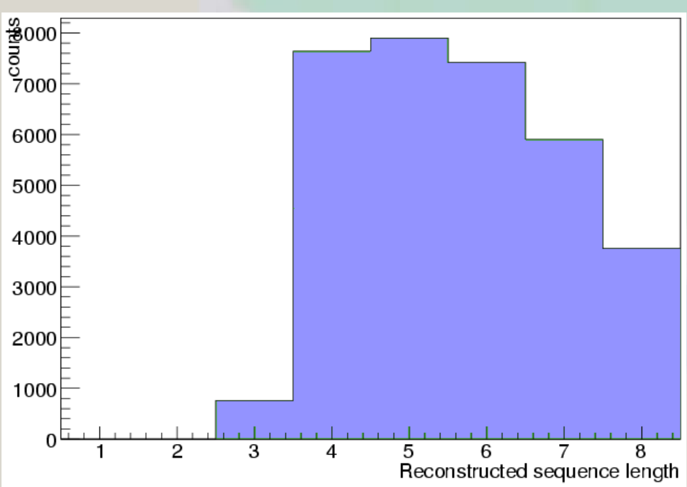
Si ACT (and variants)

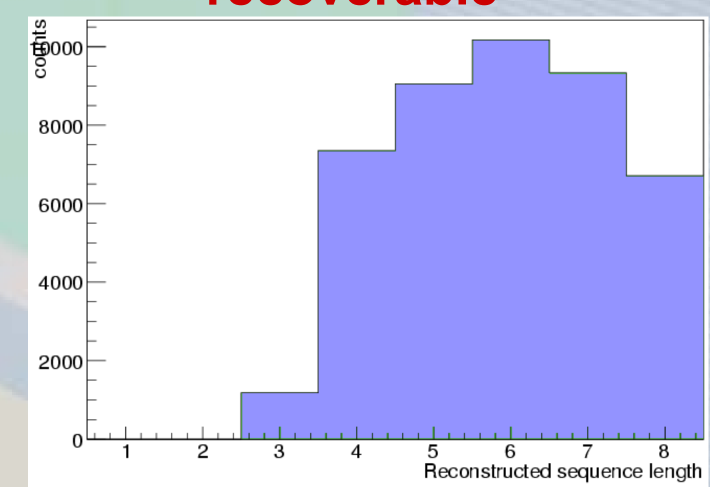
Mass model modifications

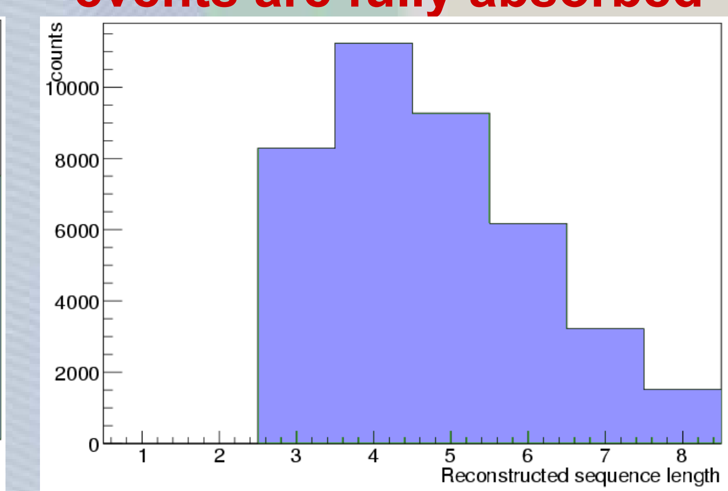
Compton sequence length for: Horizon cut 92.5^0; E = 847 +/- 22.75 keV

Insert high Z, high resolution det
Truncates scatter sequence
Preserves dE, ARM

Main Model	Thicker Si (Wafer Bonding*)	Si interleaved with CZT
64 x 3mm Si	25 x 7.5mm Si	(5mm CZT + 12 x 3mm Si) x 4
Baseline	Less dead material: longer sequences are recoverable	High-Z material interleaved: no need for longer sequences, because more events are fully absorbed







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***see N35-62: Phlips et al. for wafer bonding**

Novikova (NRL) et al. 2005 – Si ACT

Desirements for high-res Compton tele

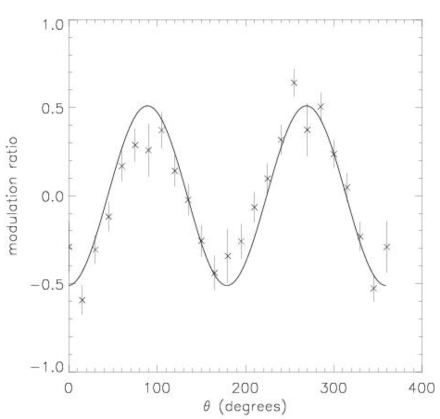
- Low Z scatterer
  - Minimizes Doppler broadening (most important below MeV)
  - Minimizes MCS of recoil electron, if tracking
- High Z absorber
  - Good stopping power to absorb scattered gamma (and minimize multi-Compton)
- High efficiency
  - Proper scatterer and absorber to give highest possible efficiency
  - Compact (as possible) to maximize geometric cross section for interaction
- Excellent energy resolution
  - Well matched with d^3x
- Fine position resolution
  - Well matched with dE
    - Thumb: ~1 mm and ~1 keV are commensurate
- Low-power electronics
  - Preserve intrinsic dE, d^3x of detectors while staying within power budget
- Minimal passive mass within detection volume
  - Interactions can be missed in passive material, and kill Compton performance
  - Minimize structural supports, co-located electronics

Polarimetry

- Compton telescope is good polarimeter
  - Compton scatter preferentially in direction perpendicular to polarization vector
  - Measure intrinsic polarization of g-ray source by measuring modulation in scatter angles in detector

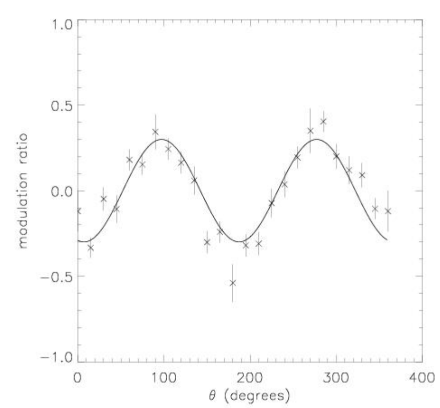
Modulation ratios for 2-layer instrument

In-plane



•High polarization ratio.
•Short lever arm.
•High geometric efficiency for thick detectors (strip pitch < thickness).
•Data more difficult to process.

Out-of-plane



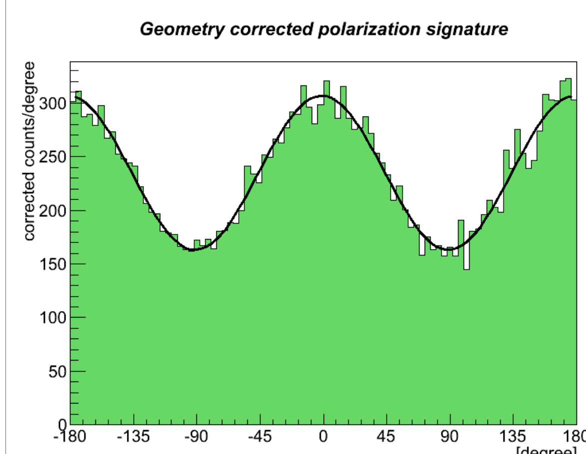
•Lower polarization ratio.
•Longer lever arm.
•Efficiency rises as ~N2.
•Data simpler to process.

Polarization response

Crab-like source (ref: Jourdain & Roques 2009)

Energy range (MeV)	Selections	Modulation μ_{100}	Source (s^{-1})	Atmosph. bgd (s^{-1})	CGB (s^{-1})	Cosmic-ray induced bgd (s^{-1})	$MDP_{3\sigma}$ (c)
0.2 – 2	2+ events without e- tracking θ_{EHC}=20°, θ_{ARM}=3.5°	0.305	28.3	15.0	61.4	7.0 (a)	0.37%
3 – 10	3+ events with e- tracking θ_{EHC}=20°, θ_{ARM}=1.5°	0.124	0.13	0.36	0.10	0.37 (b)	19.2%

(a) Activation from both primary and secondary (i.e. semi-trapped) protons; (b) Activation from primary and secondary protons + prompt reactions from primary protons, and secondary protons and leptons; (c) 3σ minimum detectable polarization for $T_{obs} = 10^6$ s



Polarigramme for a Crab-like source on axis in the range 0.2 – 2 MeV, yielding a modulation μ_{100} = 0.305

- Minimum detectable polarization:

$$MDP_{3\sigma} = \frac{3\sqrt{C_S + B}}{\mu_{100} C_S \sqrt{T_{obs}}}$$

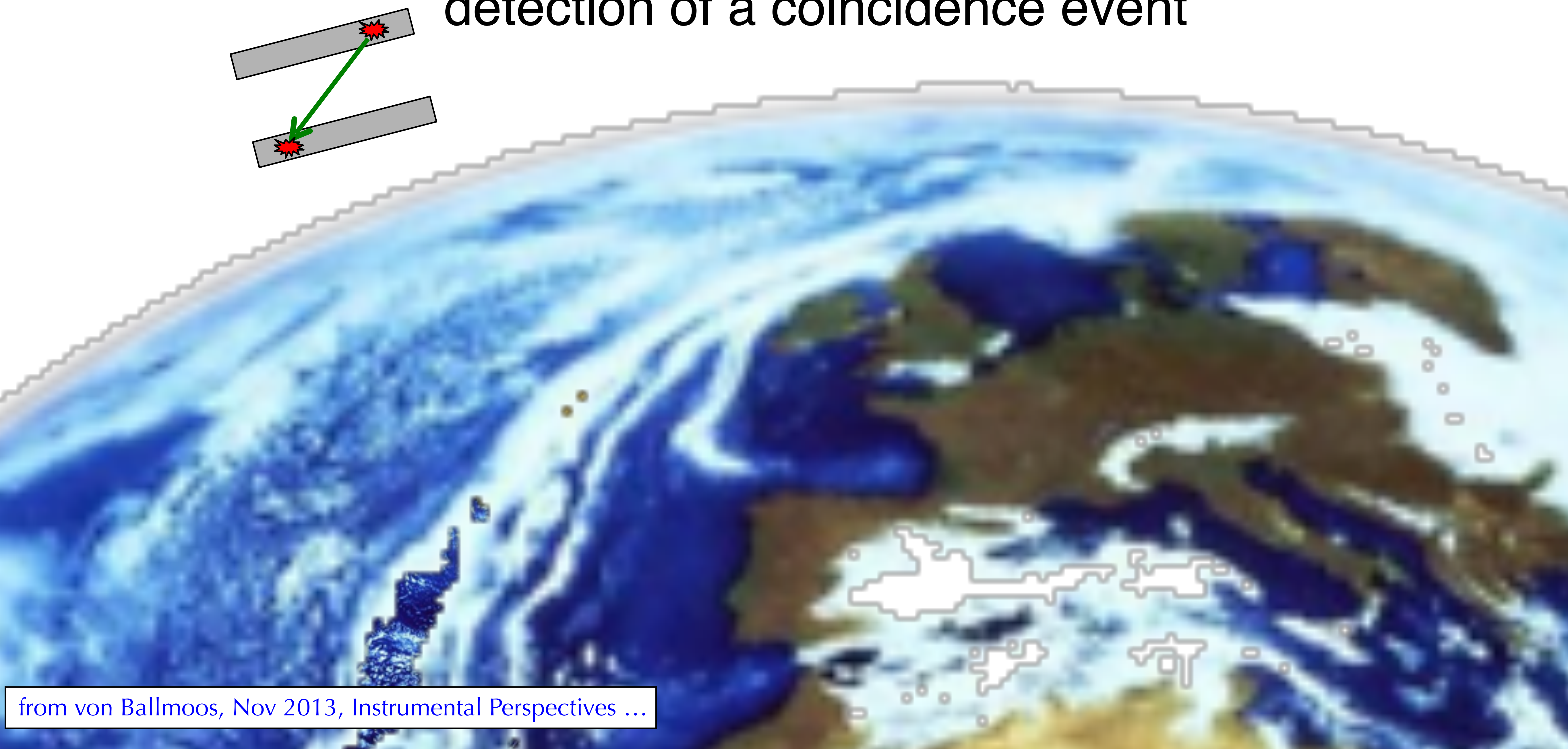
where B and C_S are the background and source count rates and μ_{100} the modulation

Compton telescopes have wide fields

detection of a coincidence event

from von Ballmoos, Nov 2013, Instrumental Perspectives …

Compton telescopes have wide fields



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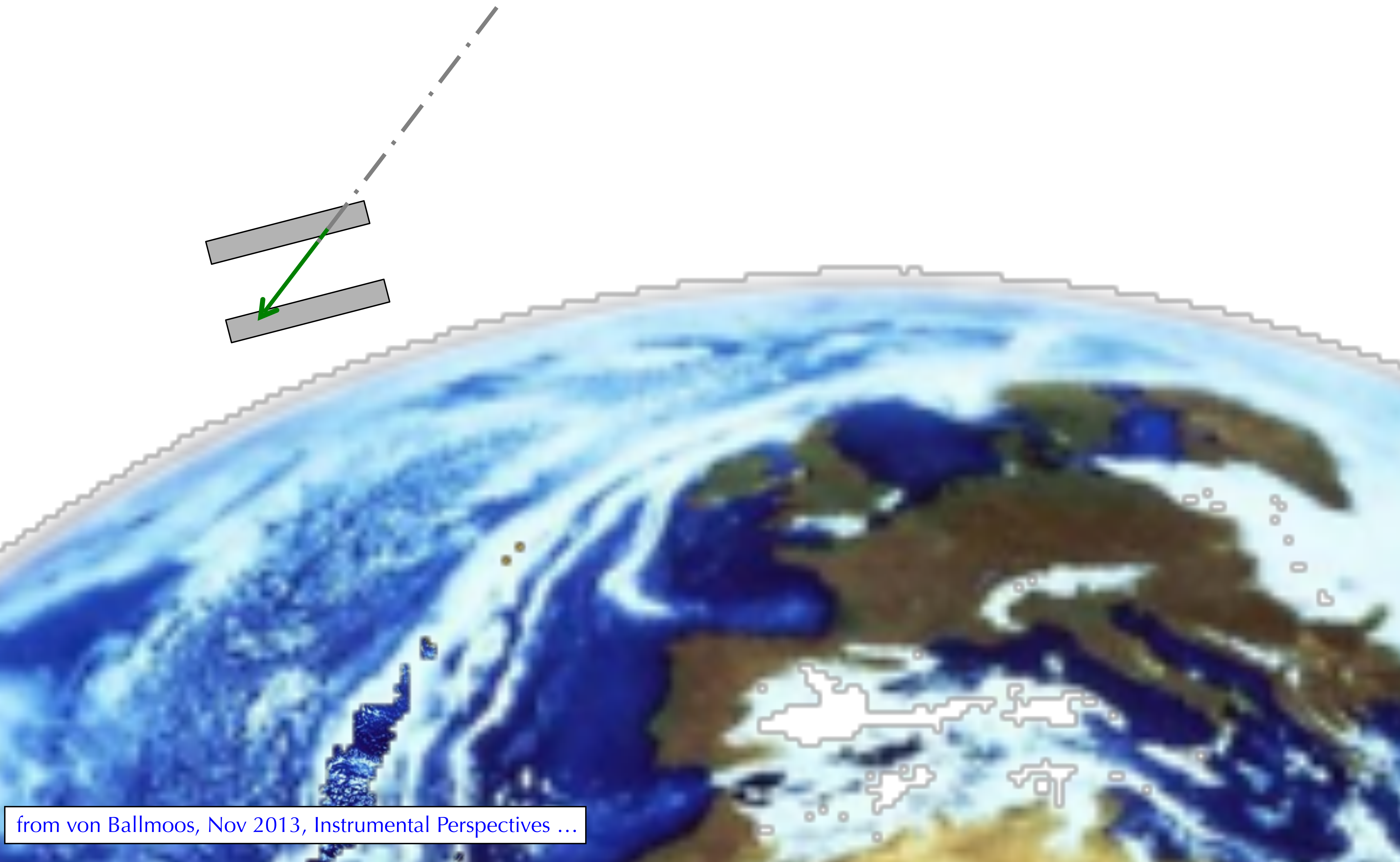

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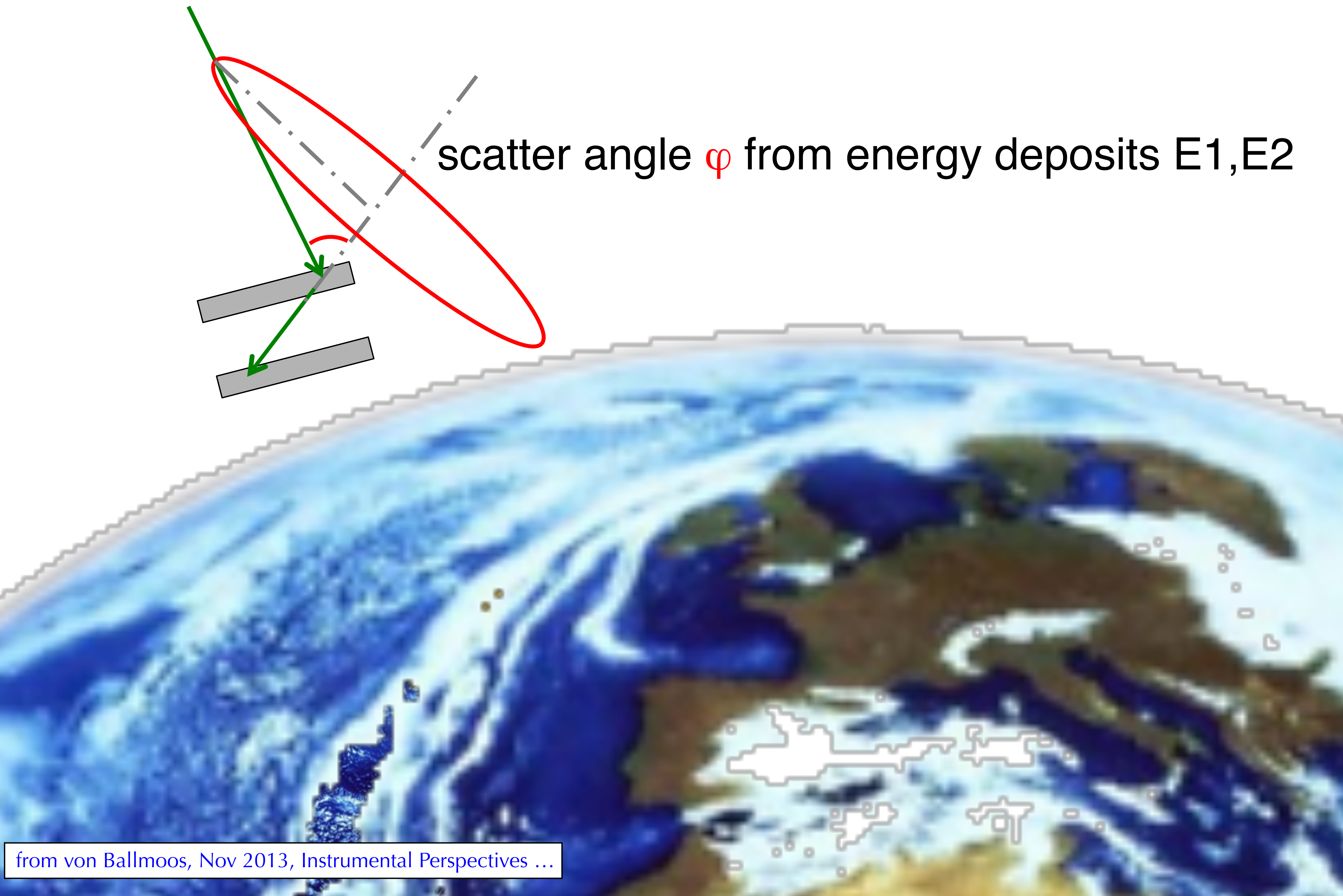
Compton telescopes have wide fields



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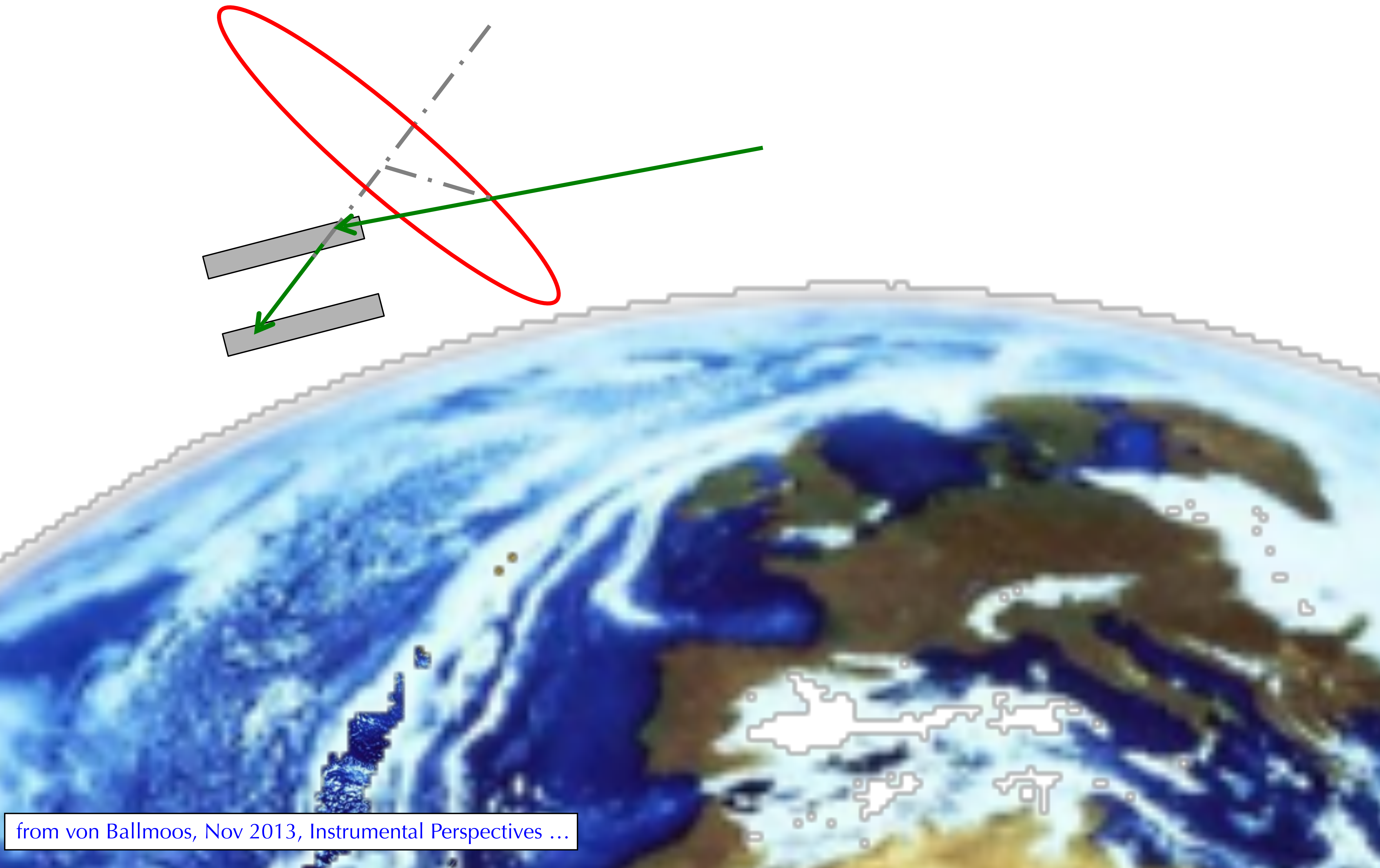
Compton telescopes have wide fields



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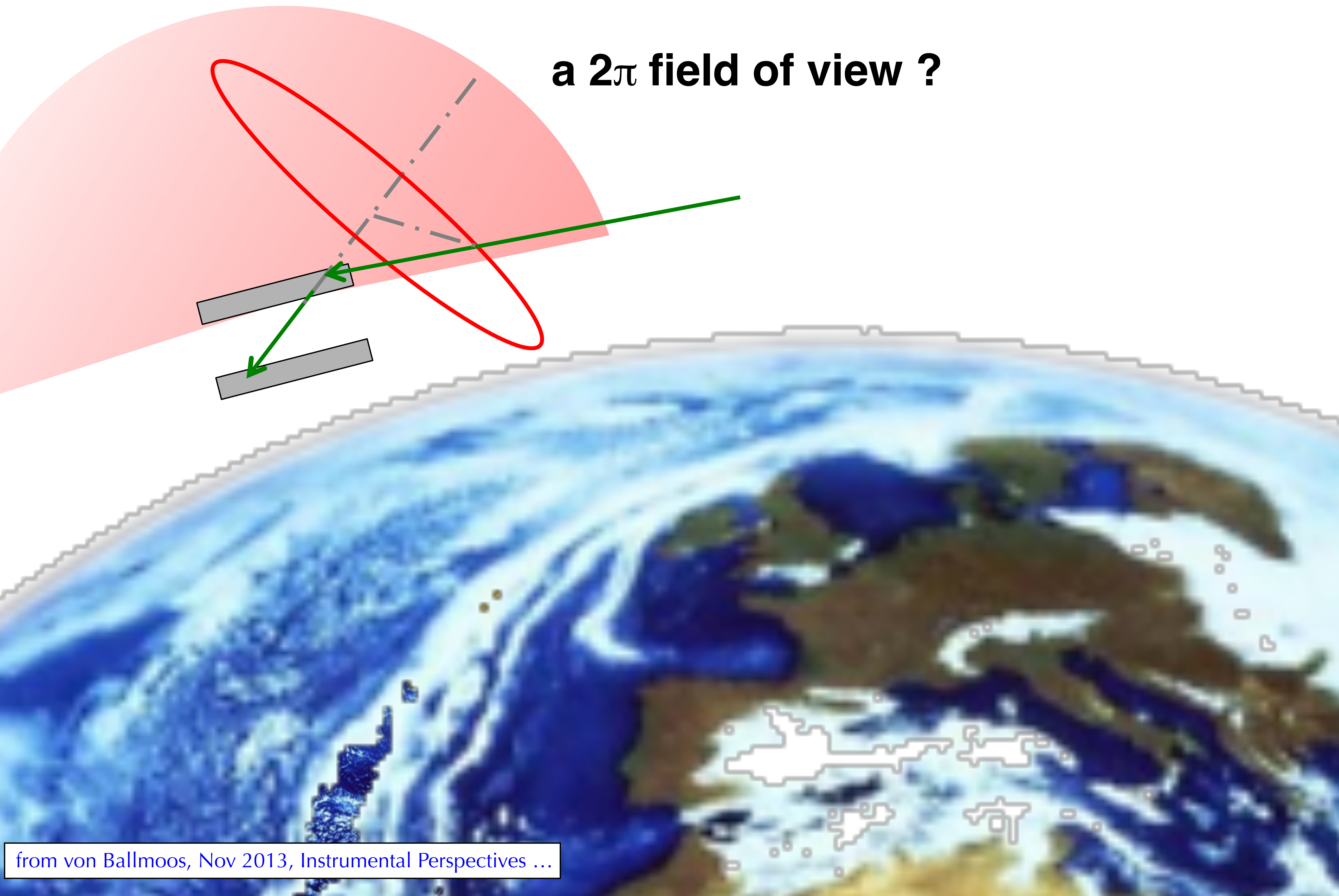
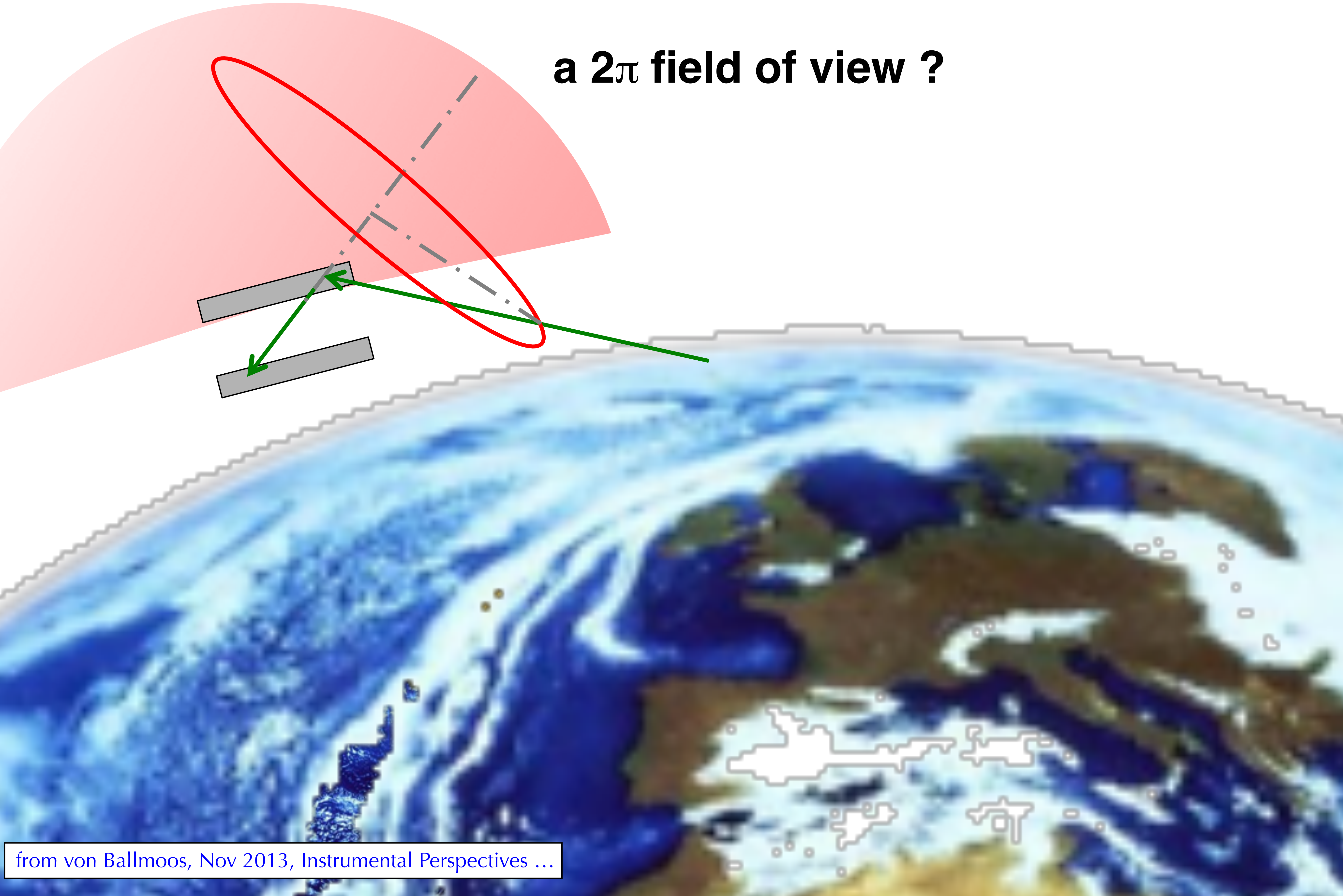
Compton telescopes have wide fields



from von Ballmoos, Nov 2013, Instrumental Perspectives …

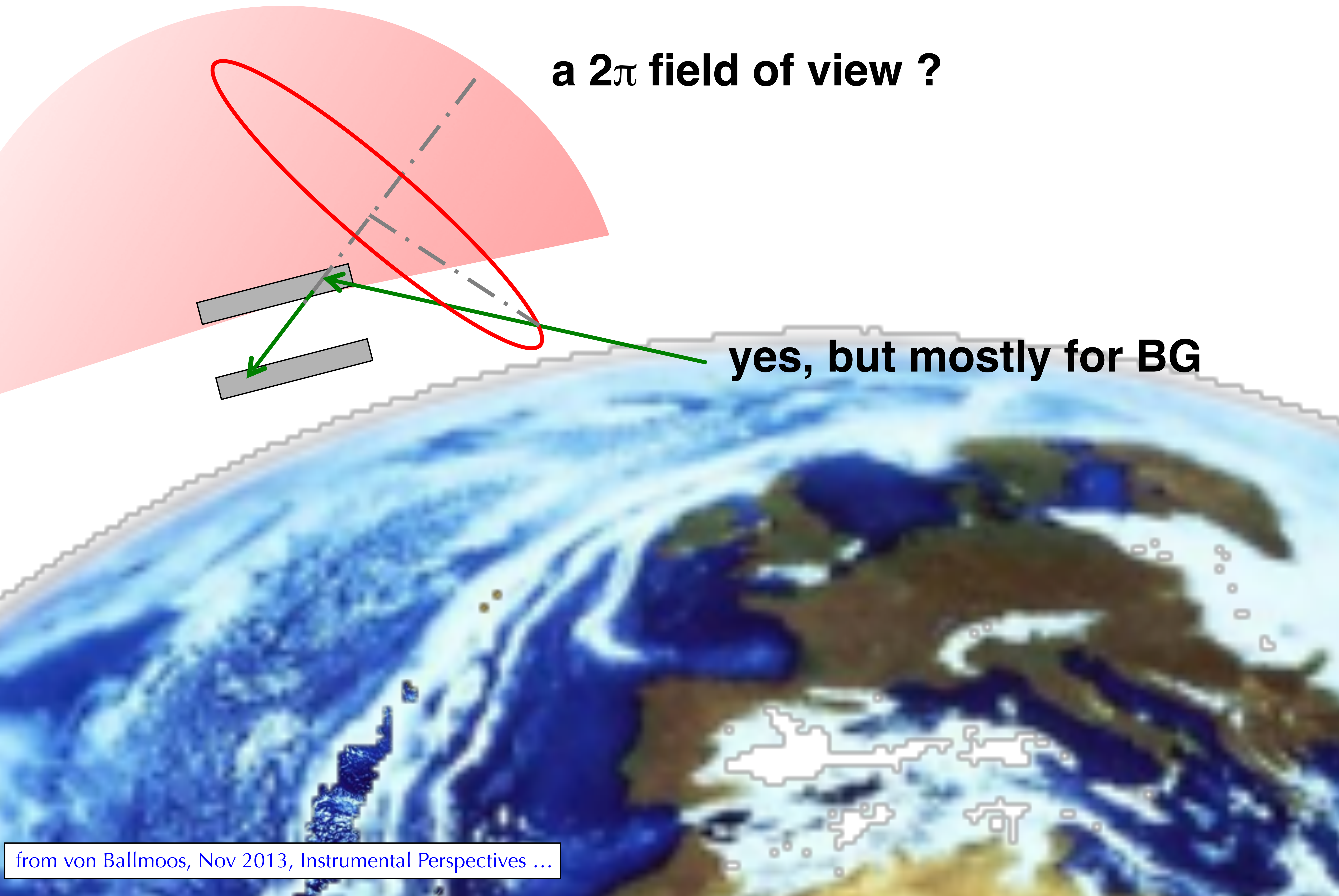
Compton telescopes have wide fields



a 2π field of view ?

from von Ballmoos, Nov 2013, Instrumental Perspectives …

Compton telescopes have wide fields

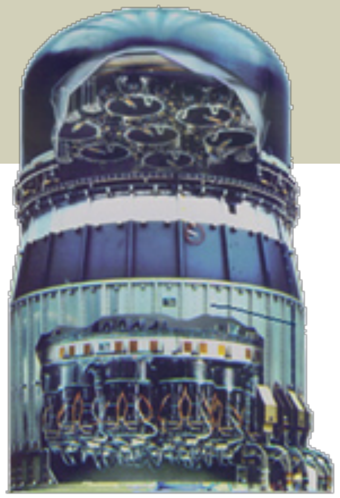


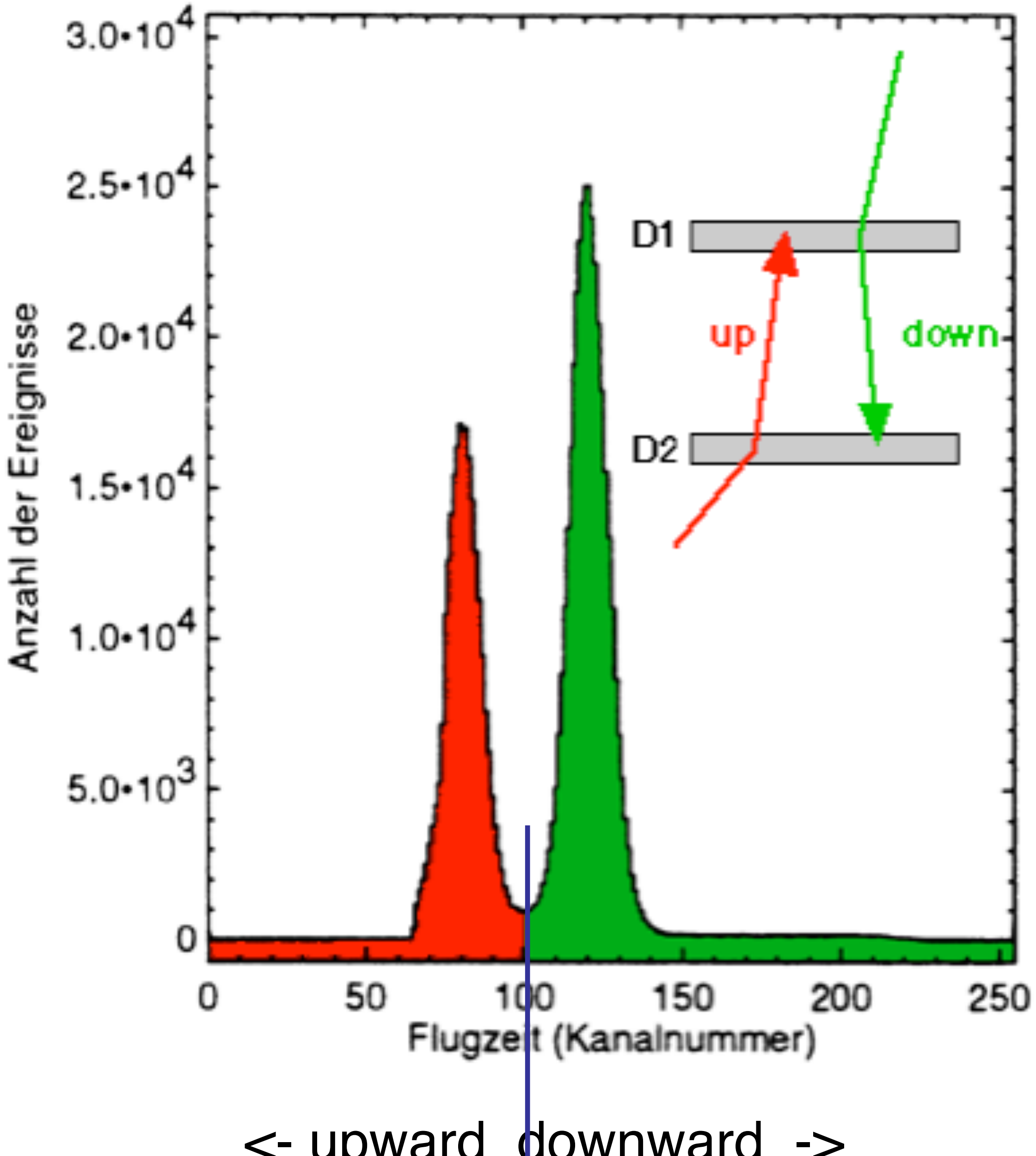
from von Ballmoos, Nov 2013, Instrumental Perspectives …

Backgrounds

- Sources of background
  - Same as LAT
    - CR primaries, trapped particles, particle albedo
    - Prompt CR secondaries
      - Atmo gammas and local gammas
        - » Beware your spacecraft, the pressure vessel on your gas TPC, etc
  - And below 10 MeV, beware radioactivities
    - Self-activity and CR-induced activation
- Mitigating the backgrounds
  - Fight the bkg
    - Shielding
      - Passive
      - Active anti-coincidence shielding
    - Bkg discrimination
      - Pattern recognition
      - Pulse shape discrimination
      - Time-of-flight
  - Avoid the bkg
    - Optimal orbit
    - Minimize passive material
    - Choose low-bkg materials

Time of Flight coincidence - COMPTEL data





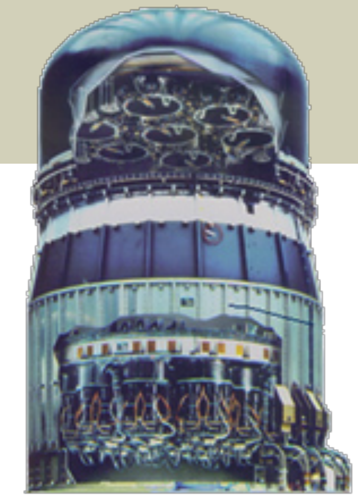
<- upward downward ->

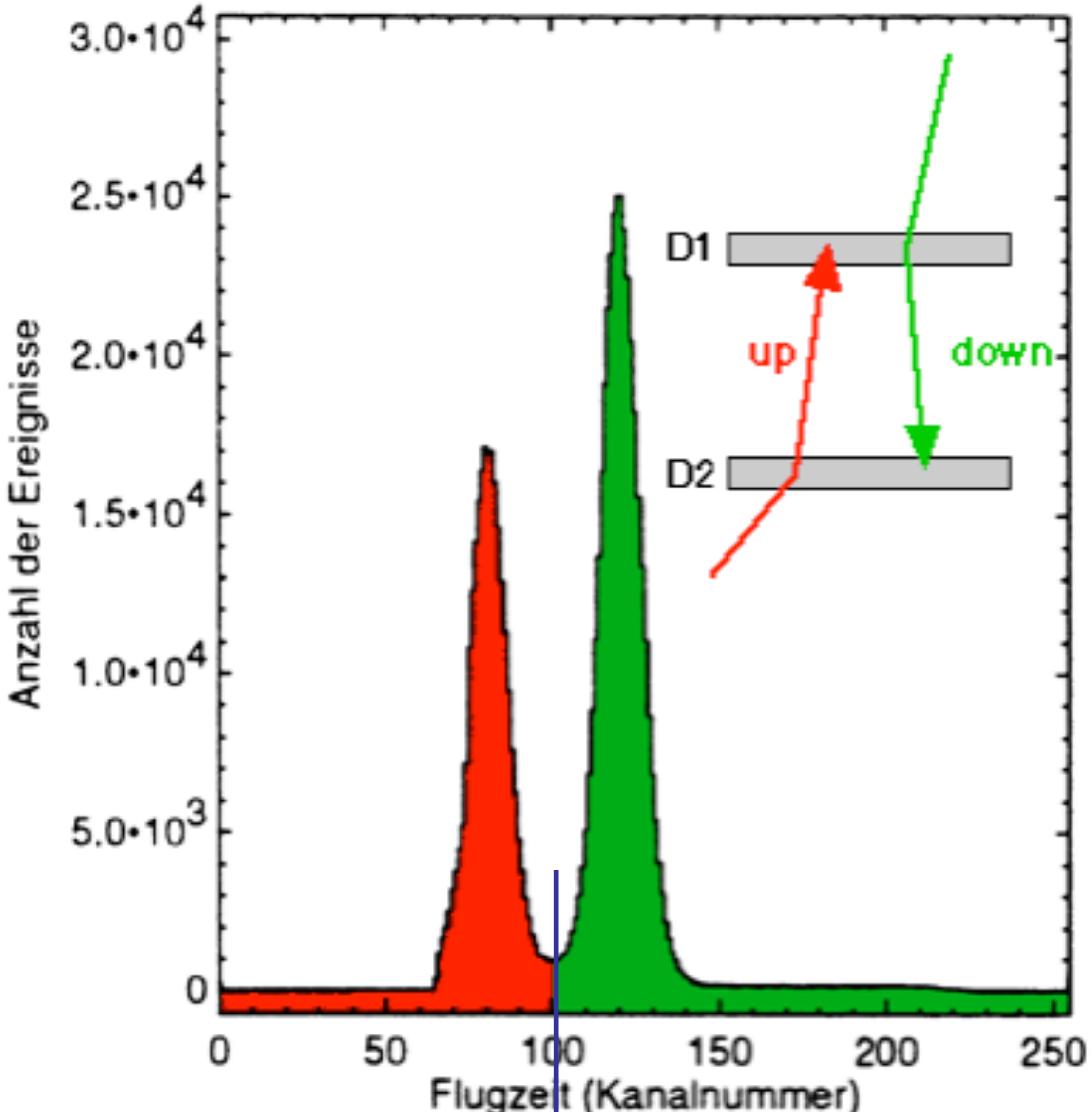
COMPTEL calibration data

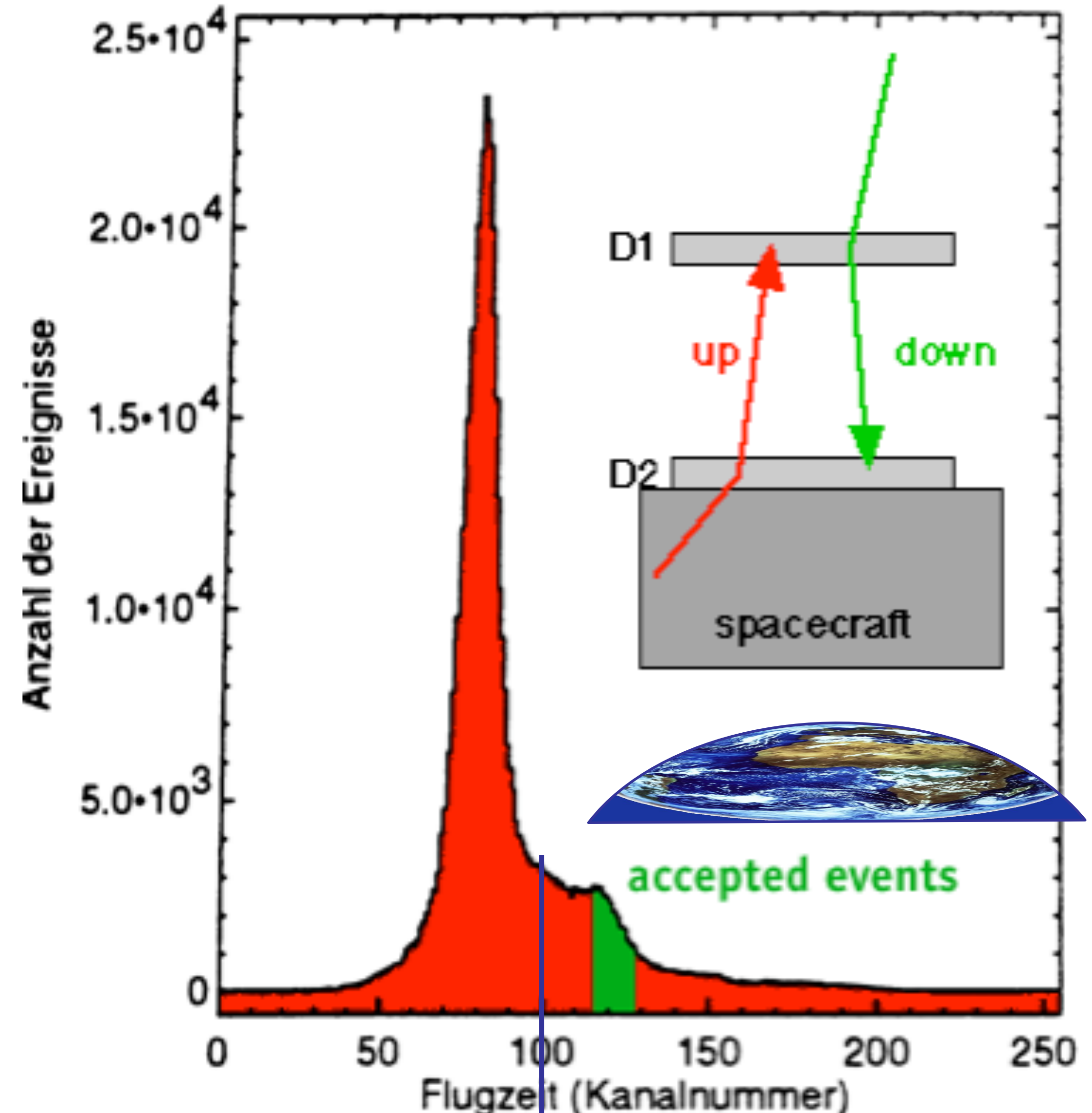
channel width : 0.25 ns
distance D1-D2 : 1.5 m ≈> 5 ns)

from von Ballmoos, Nov 2013, Instrumental Perspectives …

Time of Flight coincidence - COMPTEL data







<- upward downward ->

COMPTEL calibration data

channel width : 0.25 ns
distance D1-D2 : 1.5 m ≈> 5 ns)

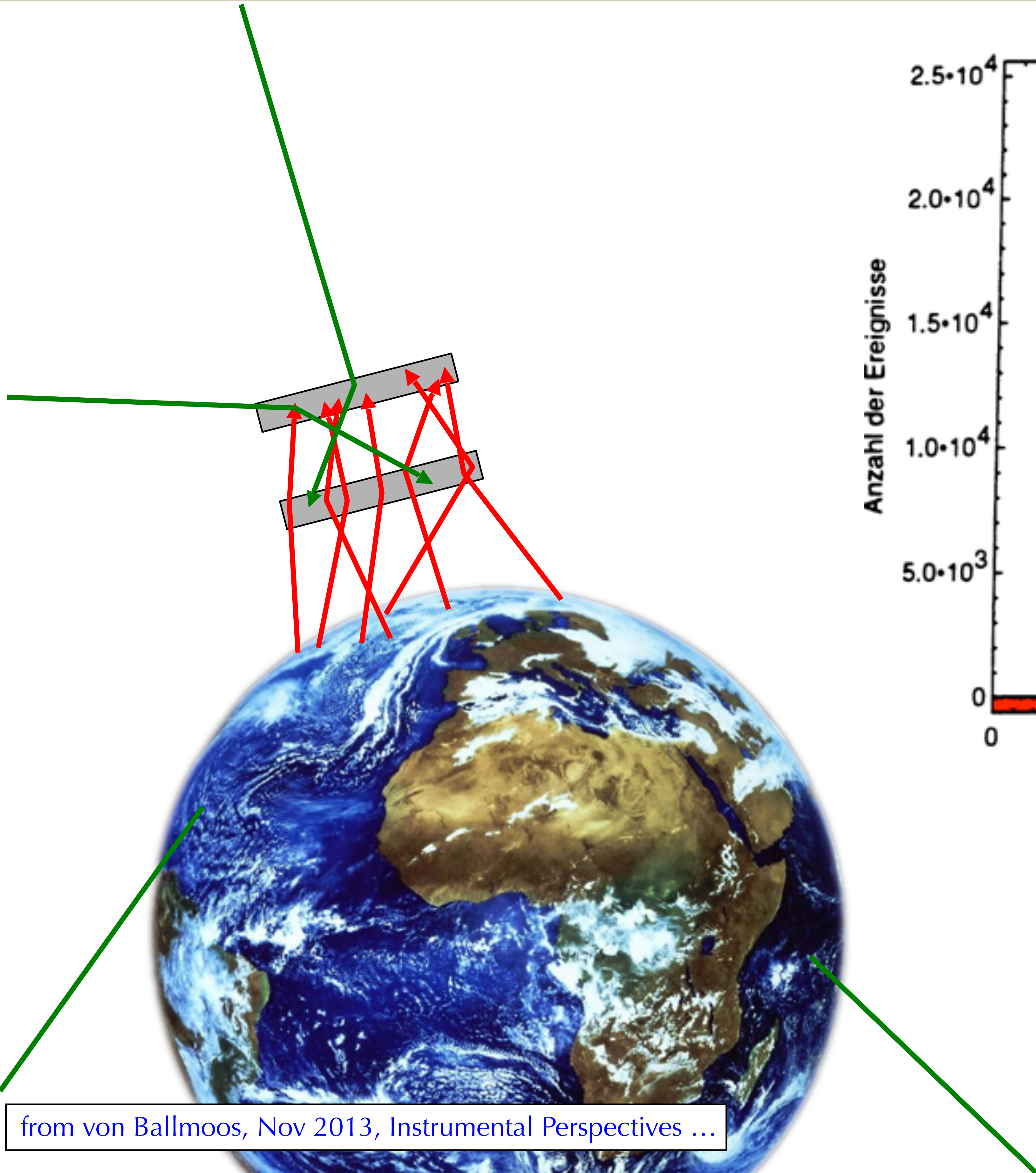
<- upward downward ->

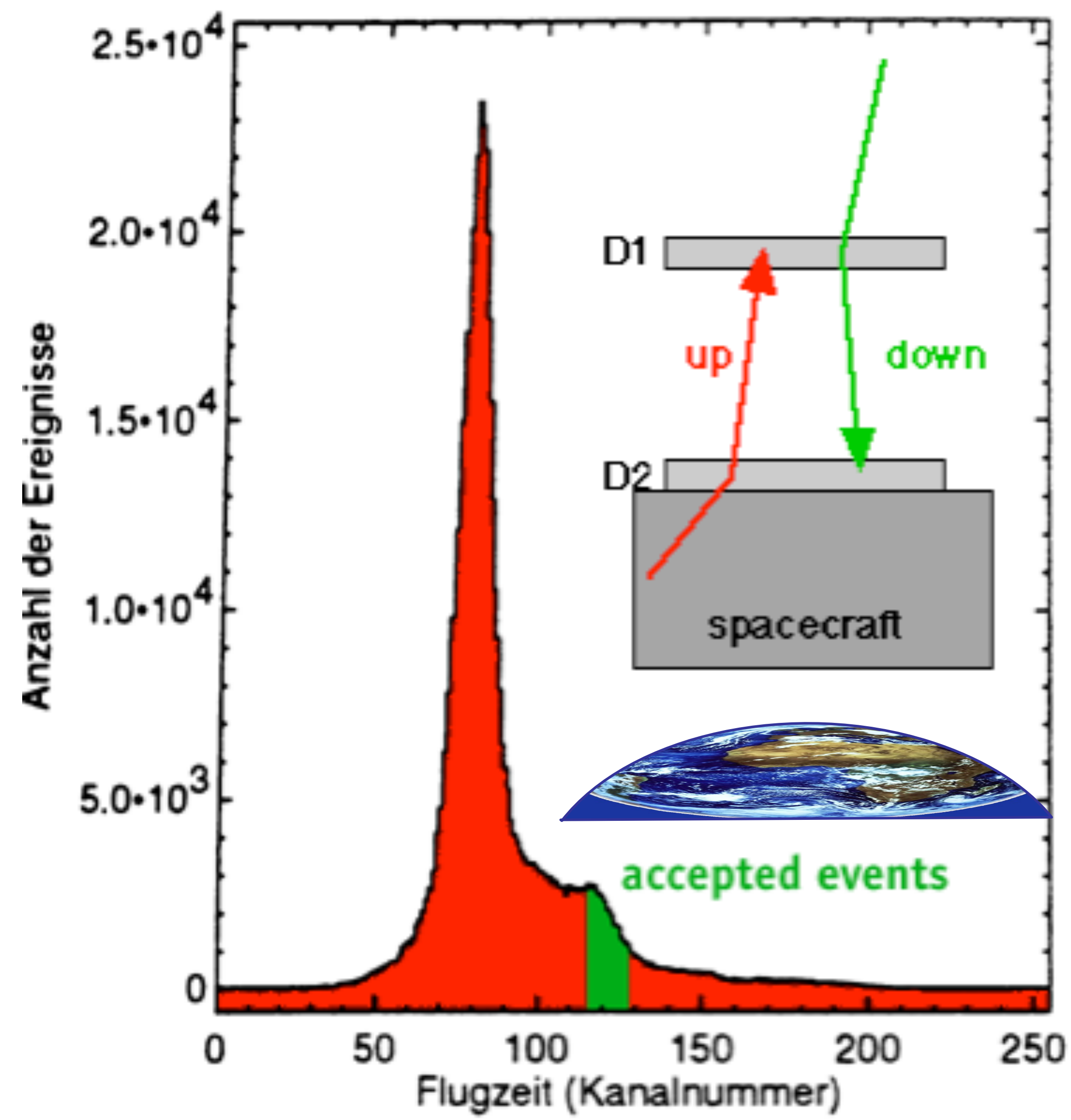
COMPTEL flight data

channel width : 0.25 ns
“upward bkg” from spacecraft and Earth

from von Ballmoos, Nov 2013, Instrumental Perspectives …

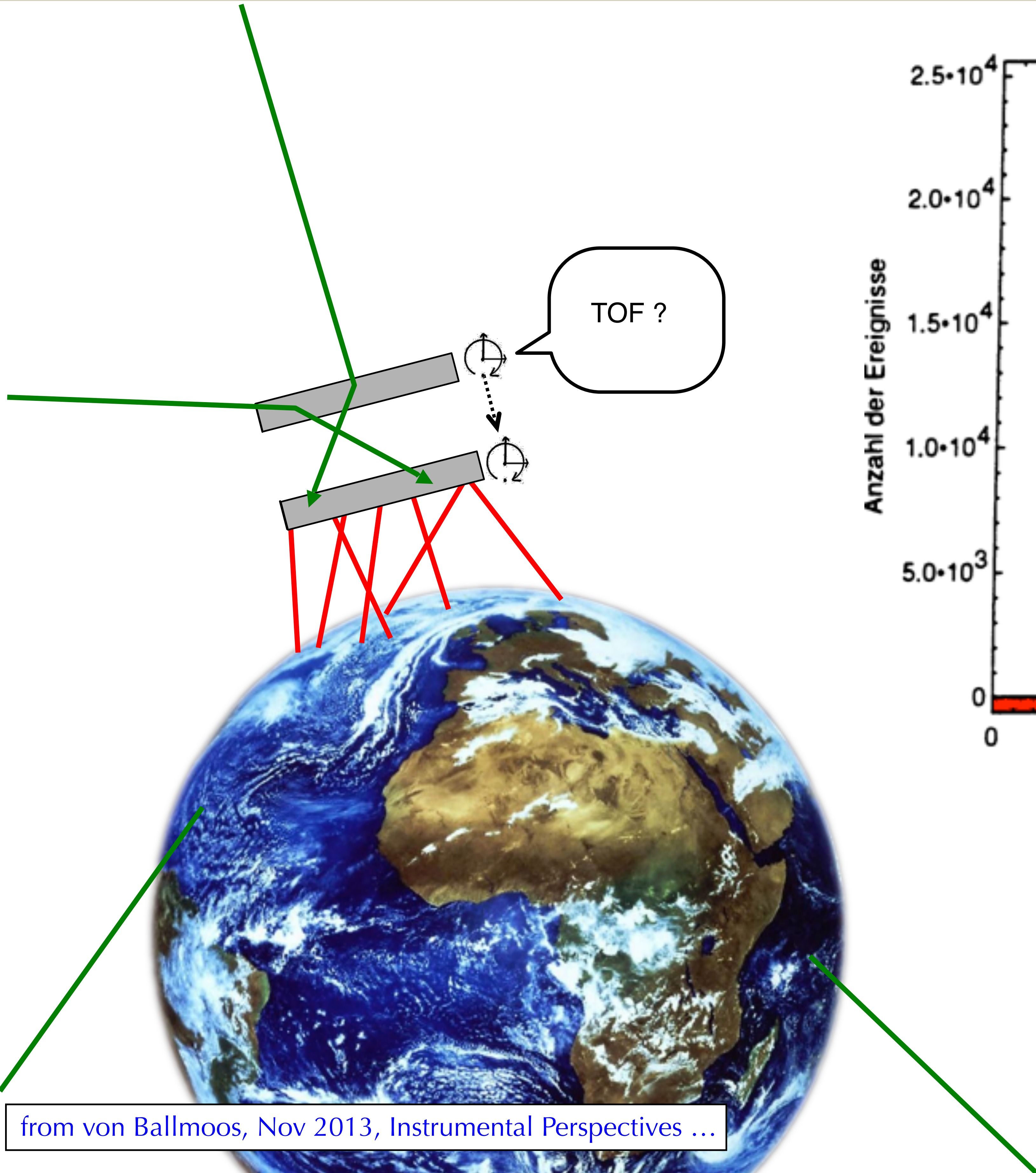
option A : time-of-flight electronics

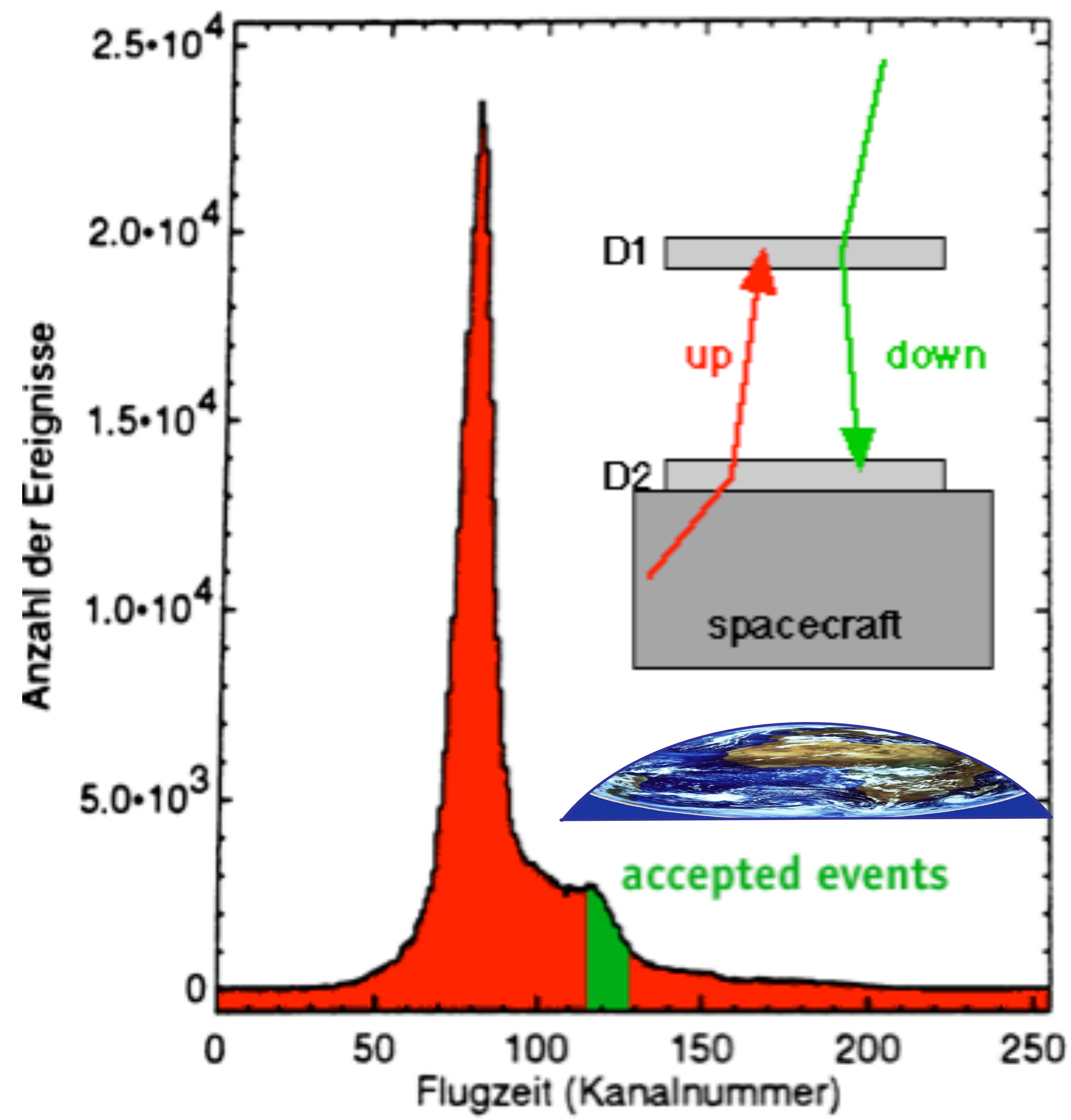




from von Ballmoos, Nov 2013, Instrumental Perspectives …

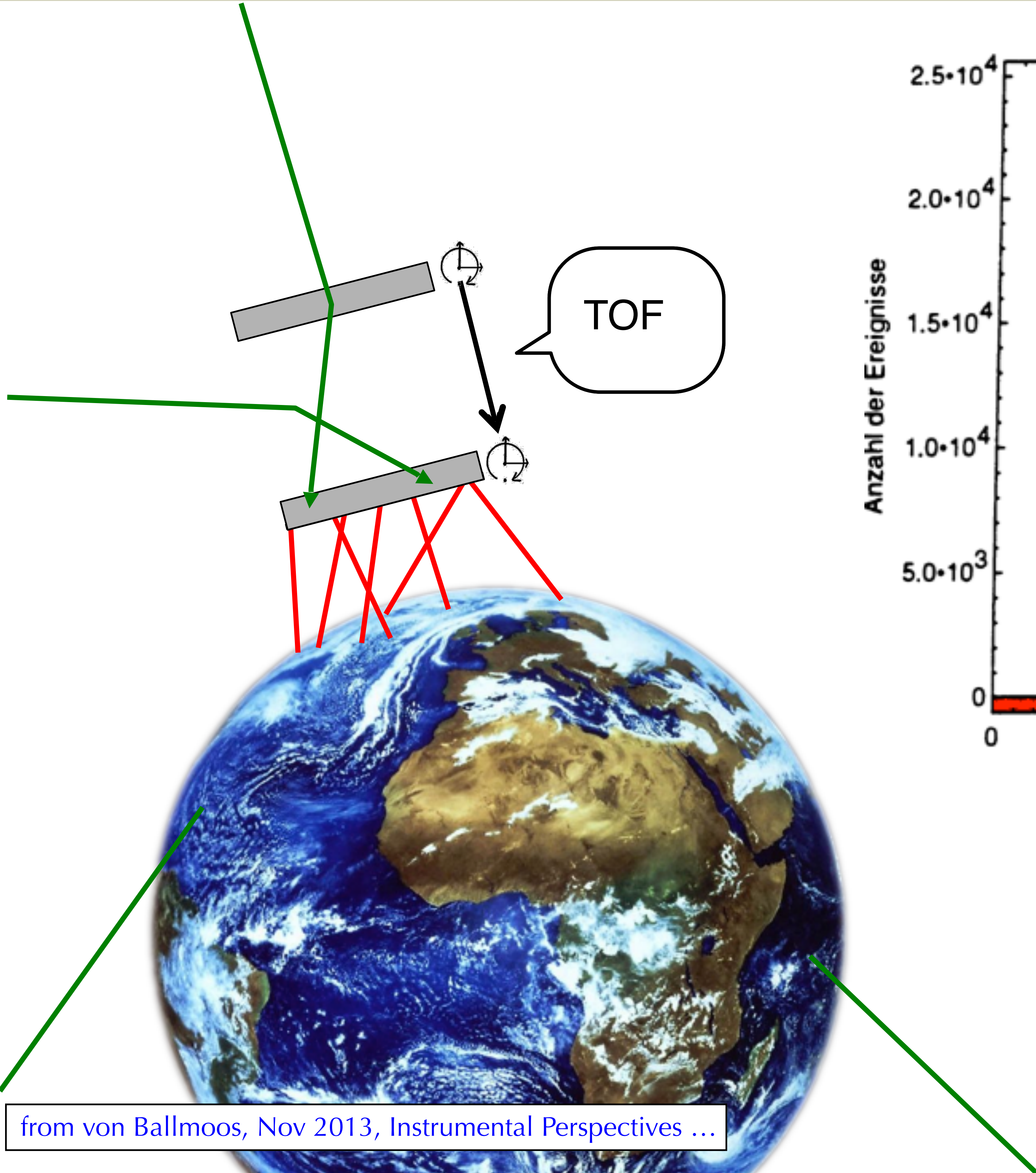
option A : time-of-flight electronics

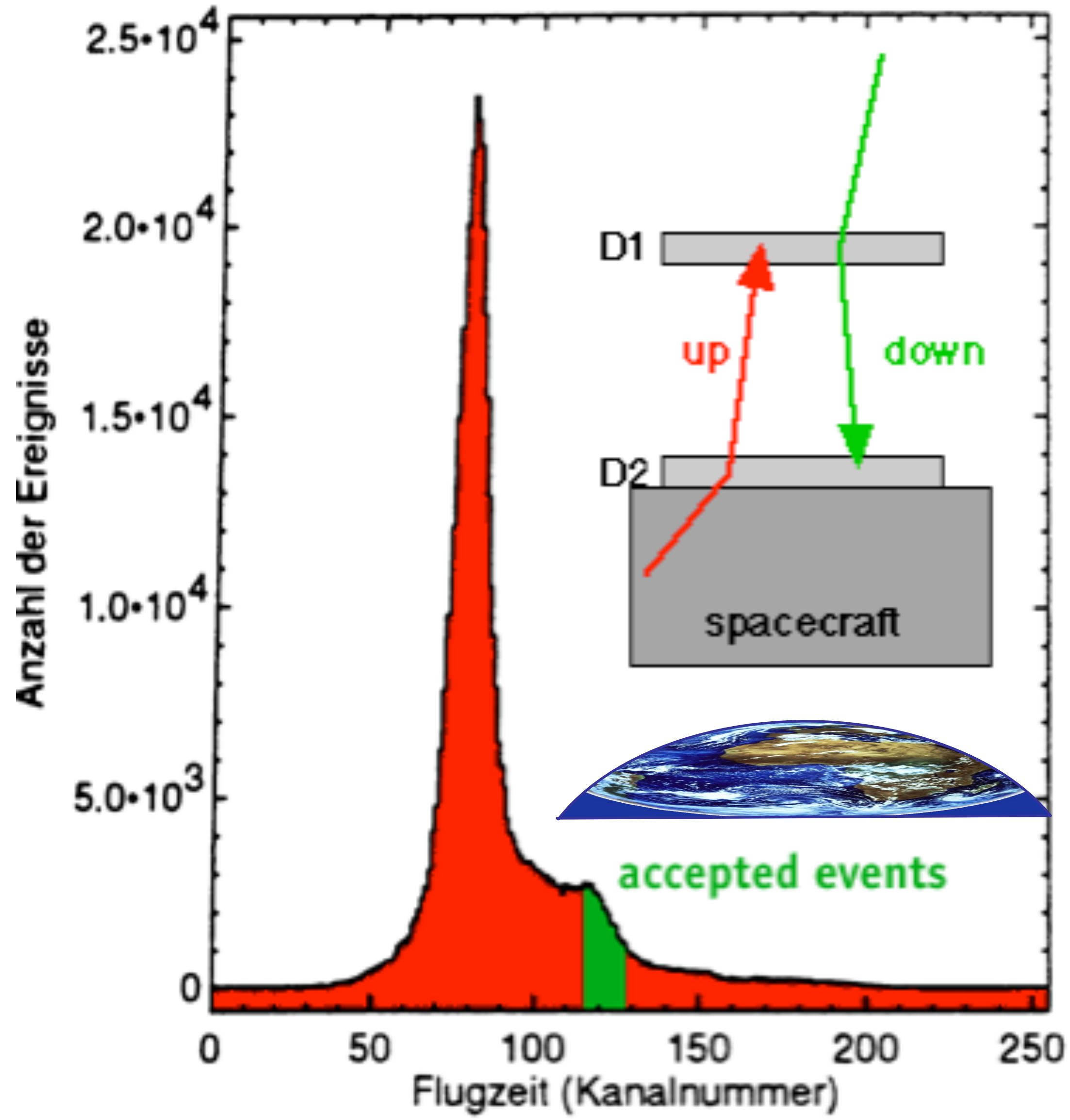




from von Ballmoos, Nov 2013, Instrumental Perspectives ...

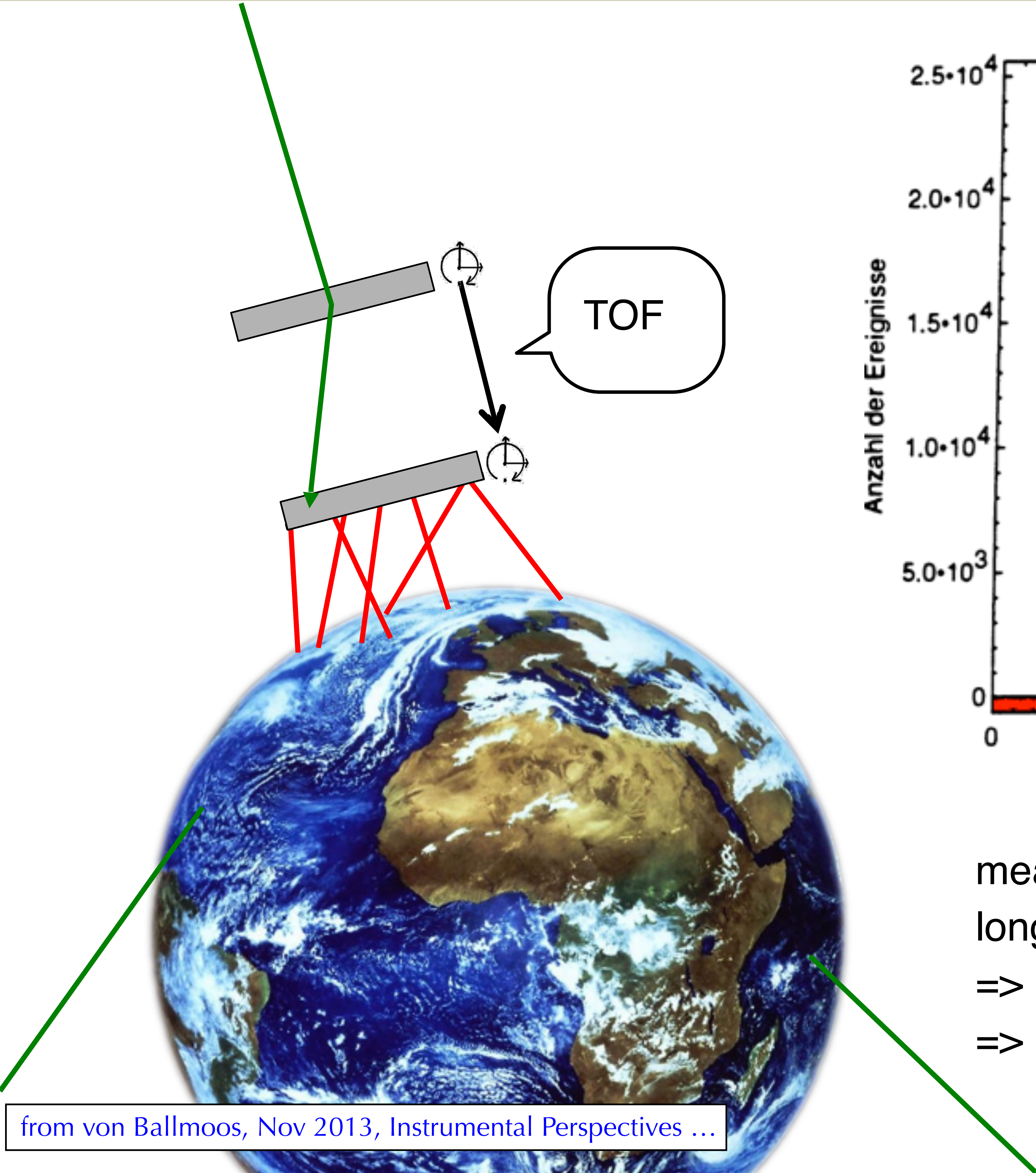
option A : time-of-flight electronics

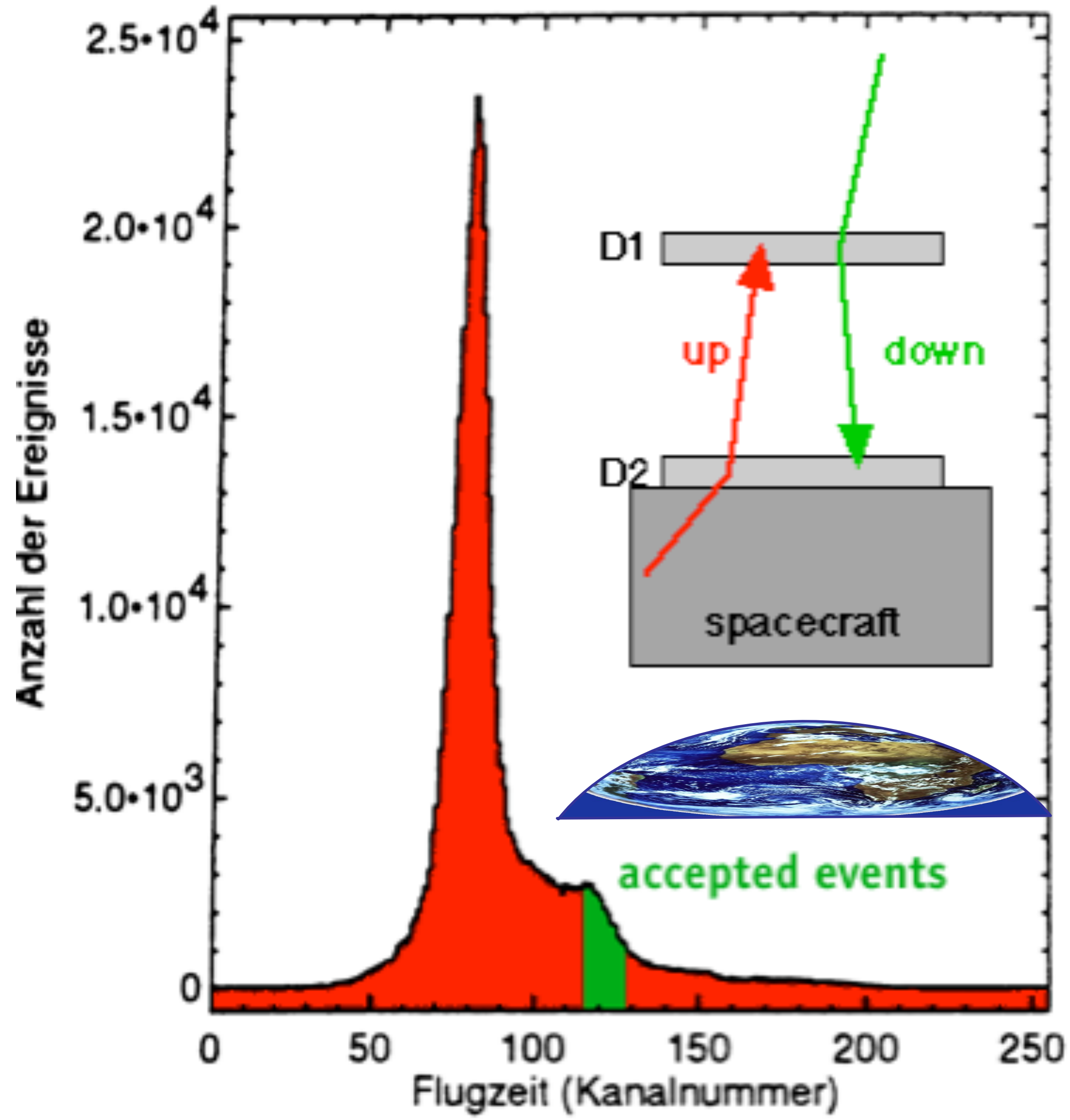




from von Ballmoos, Nov 2013, Instrumental Perspectives …

option A : time-of-flight electronics

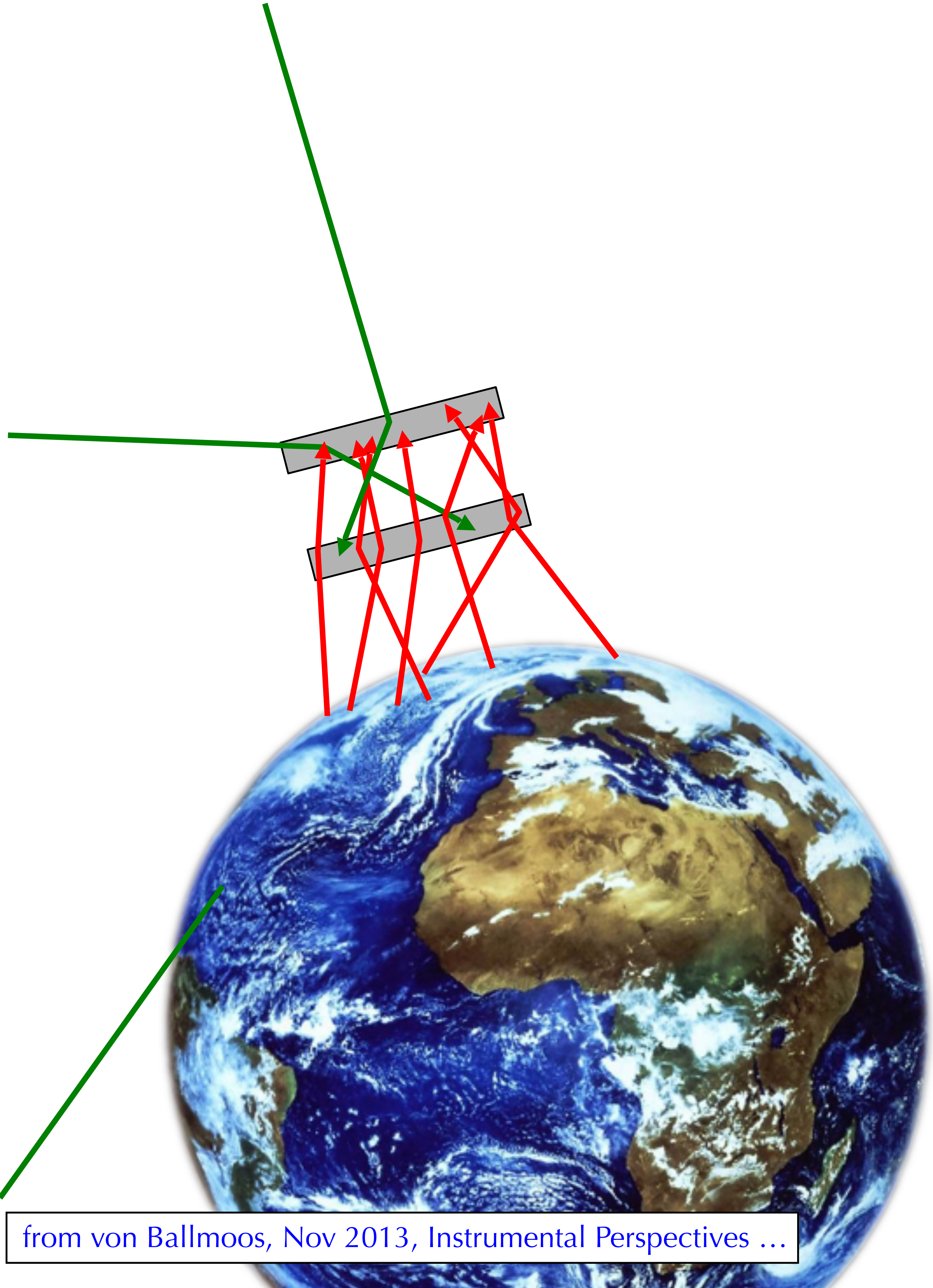


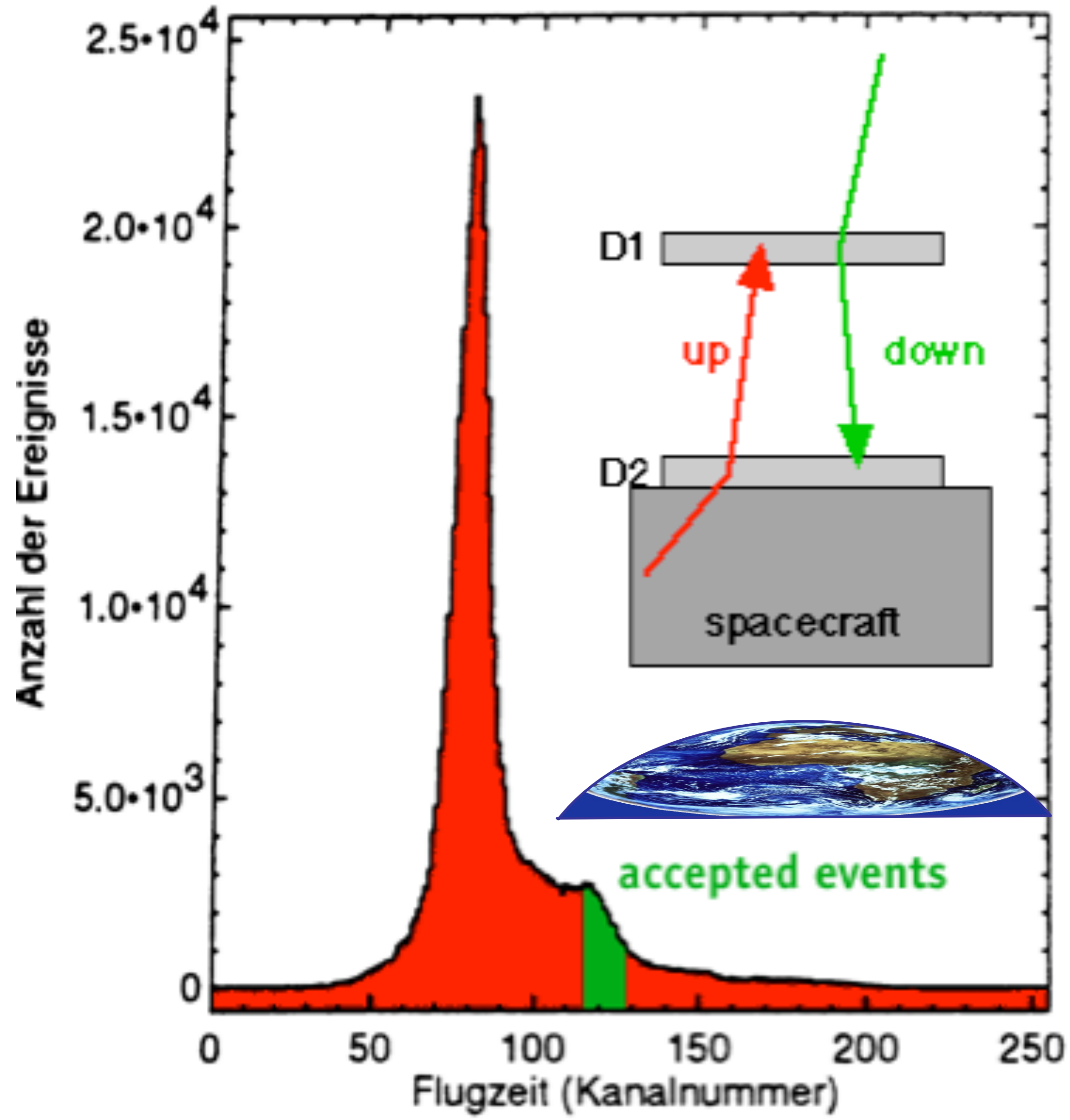


measuring TOFs requires
long baselines between D1 and D2
=> low probability for coincidence
=> **low efficiencies** (few % at most)

from von Ballmoos, Nov 2013, Instrumental Perspectives …

option B : anticoincidence shield





from von Ballmoos, Nov 2013, Instrumental Perspectives …

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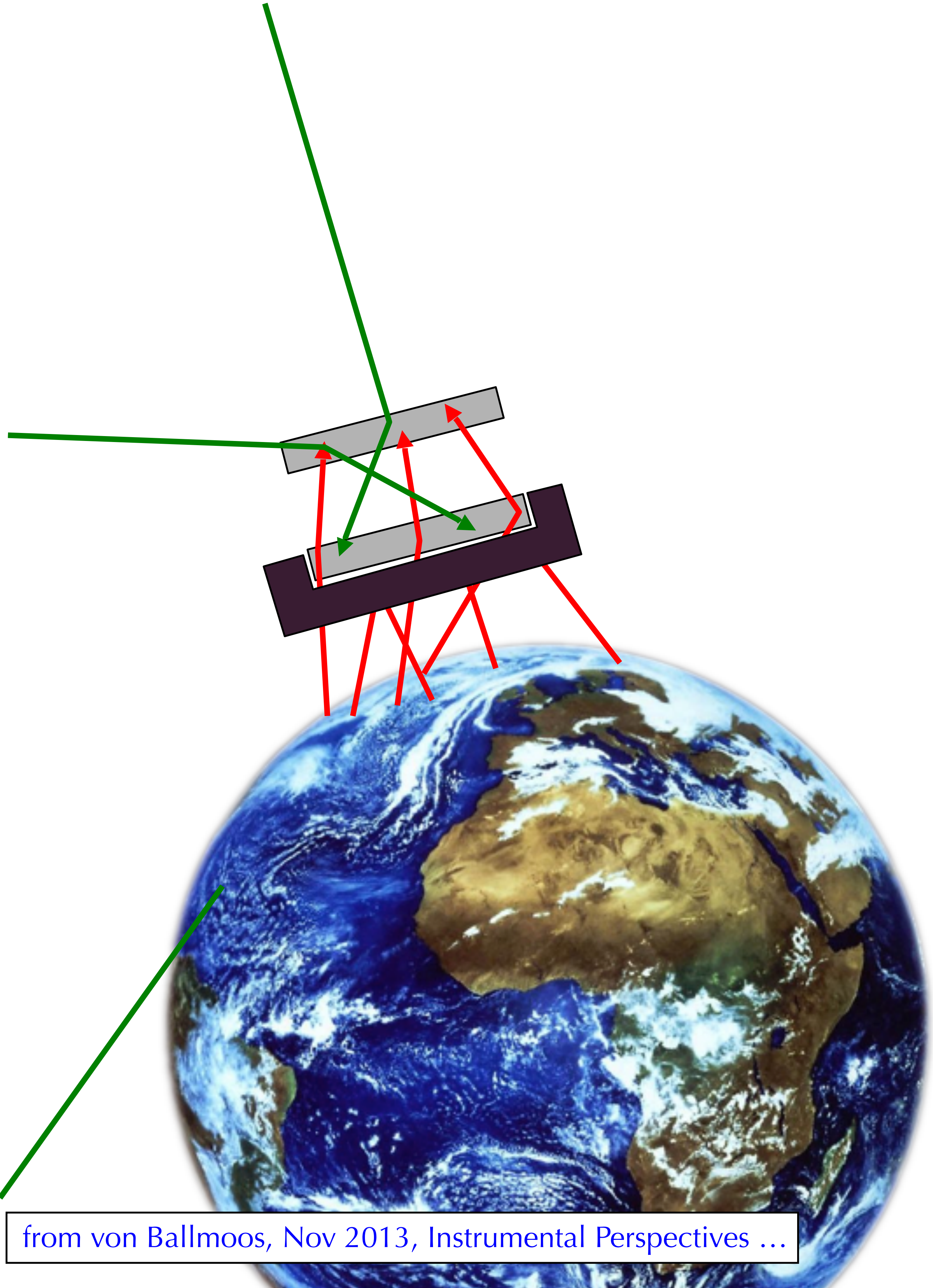

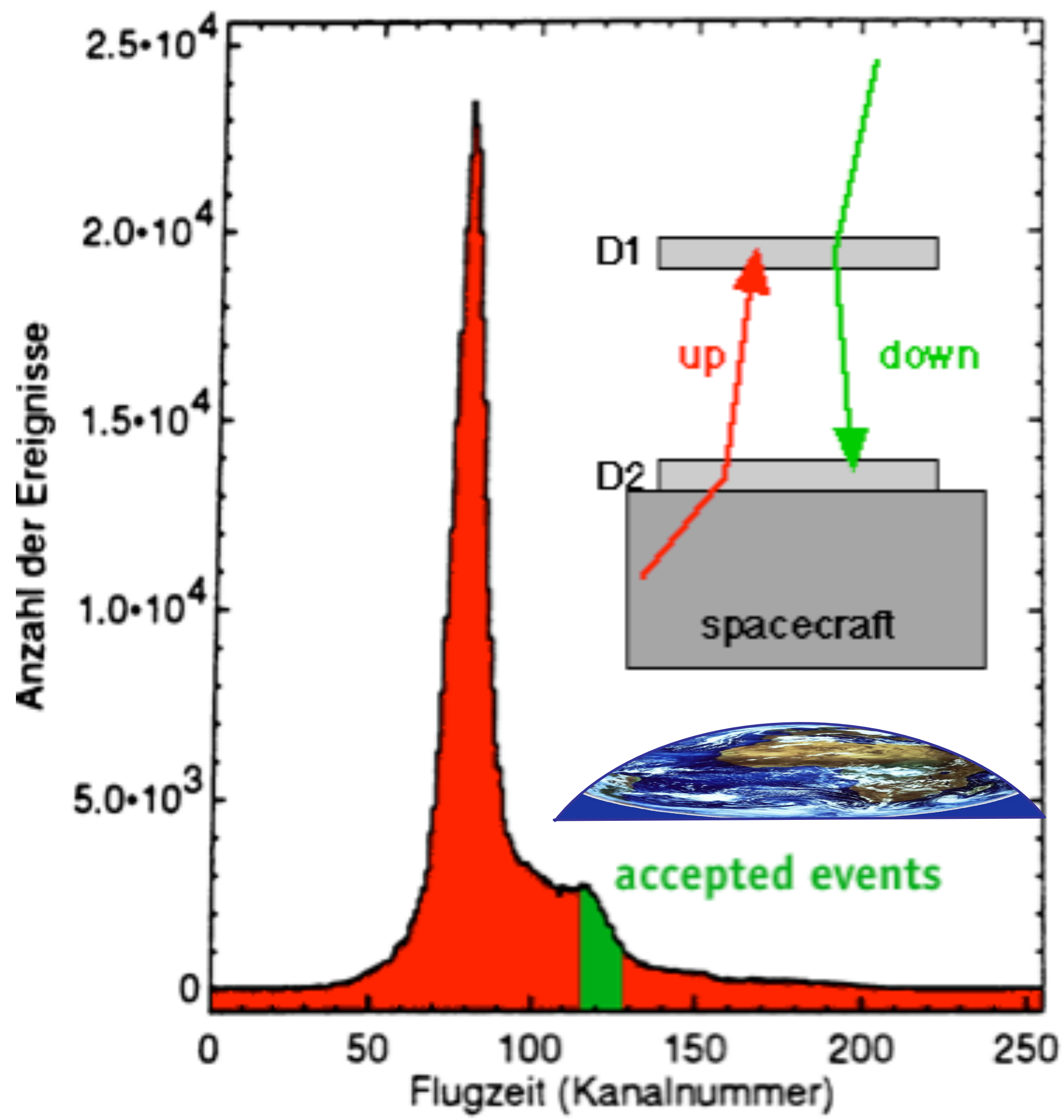

from von Ballmoos, Nov 2013, Instrumental Perspectives …

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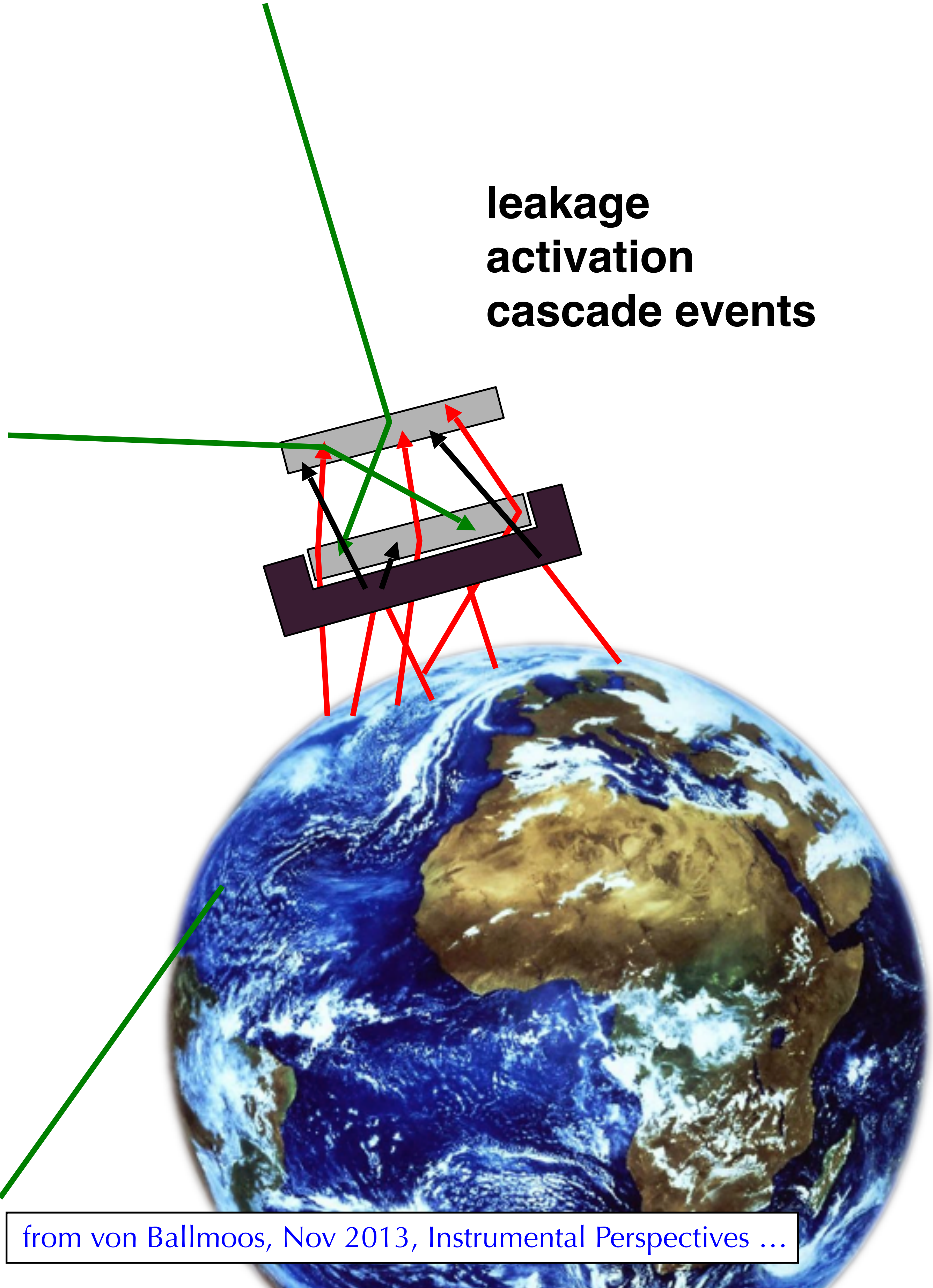

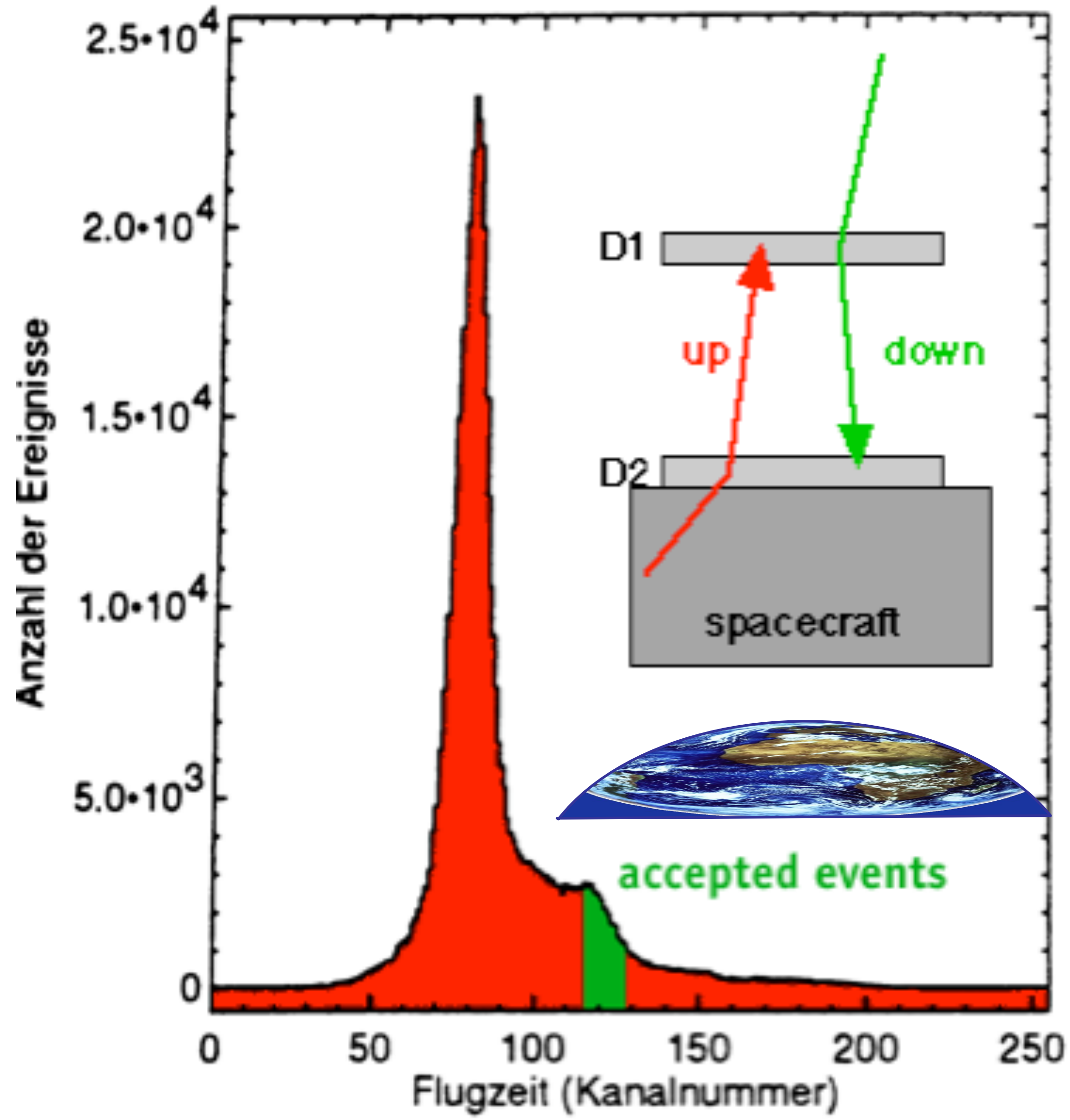

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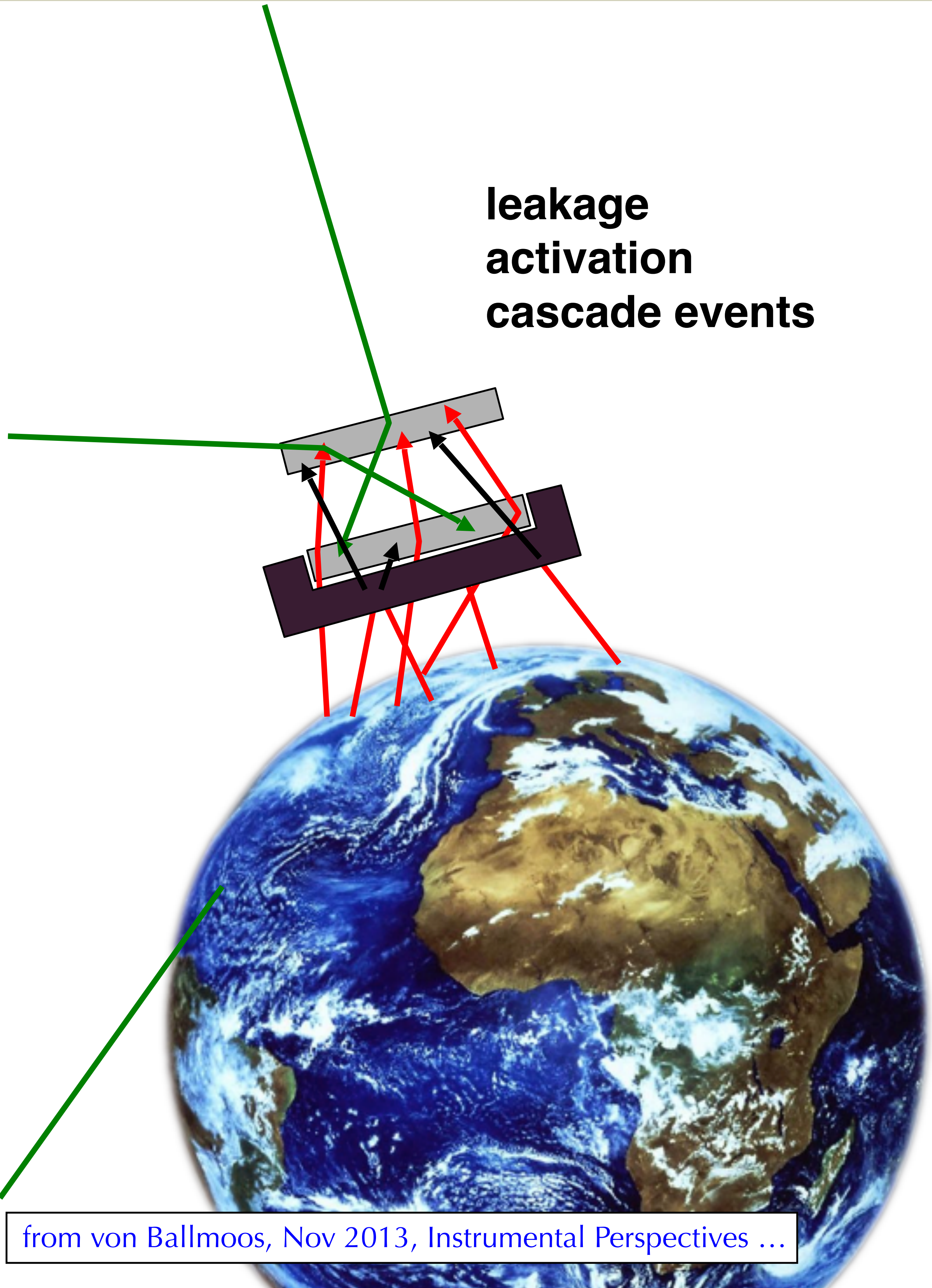
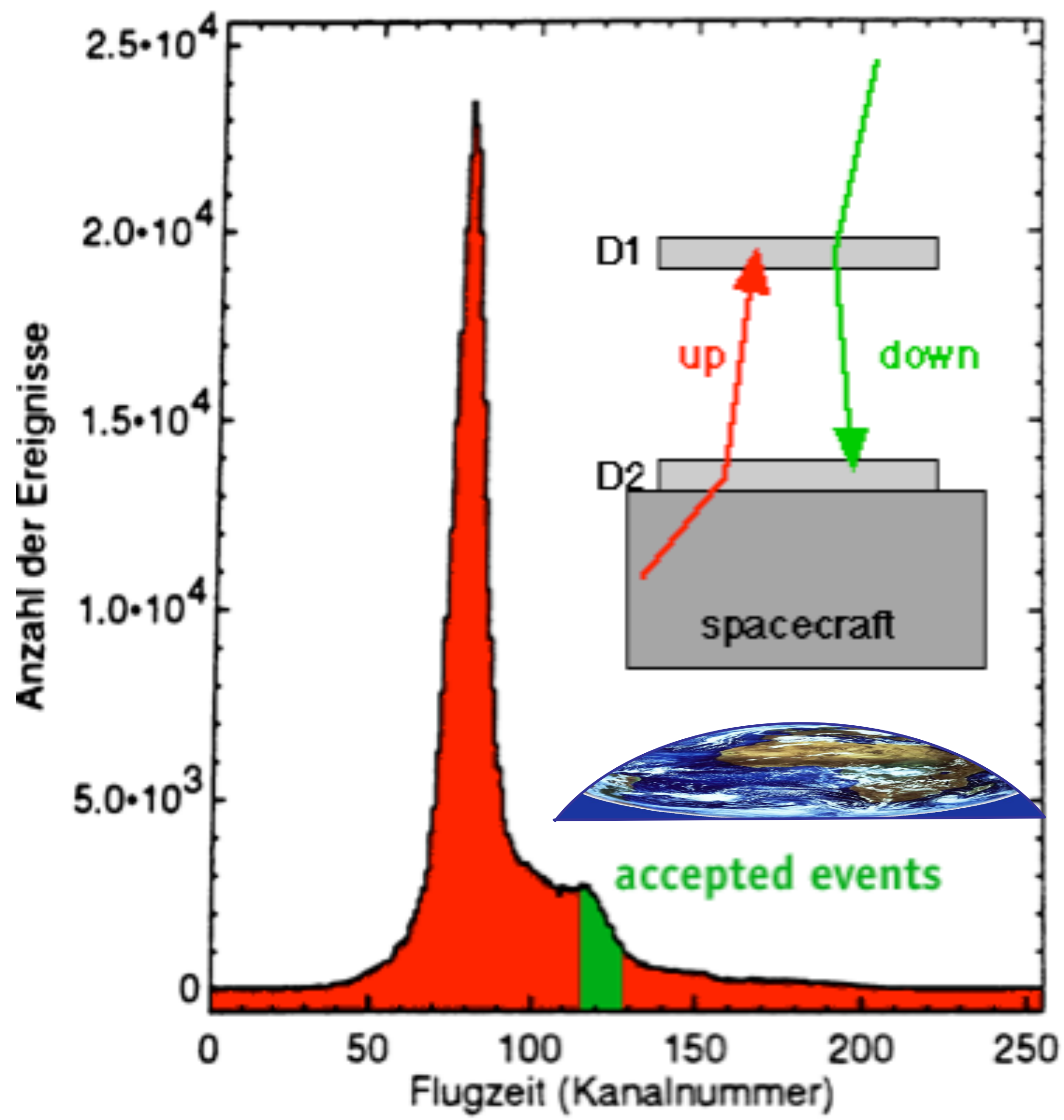
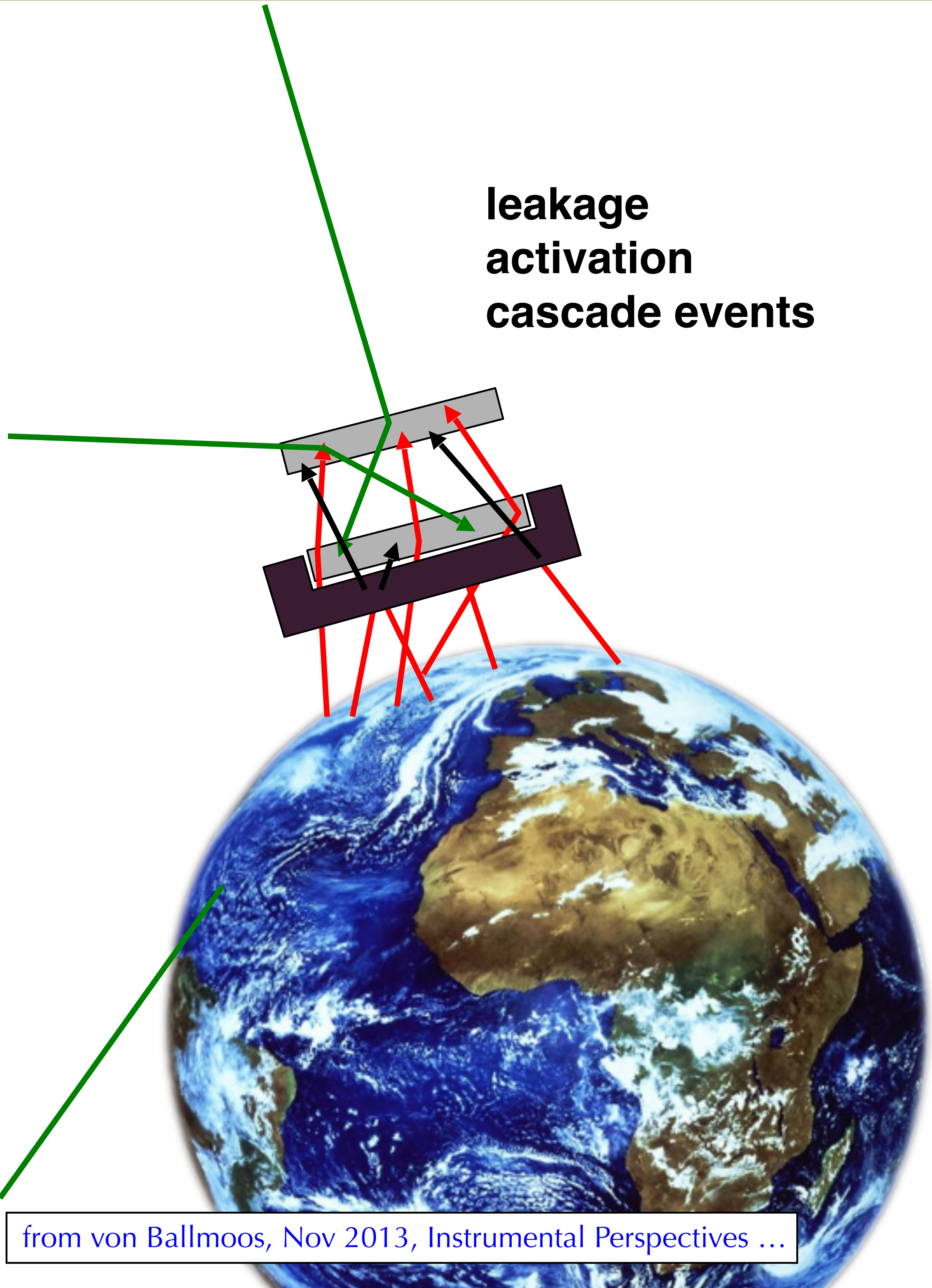


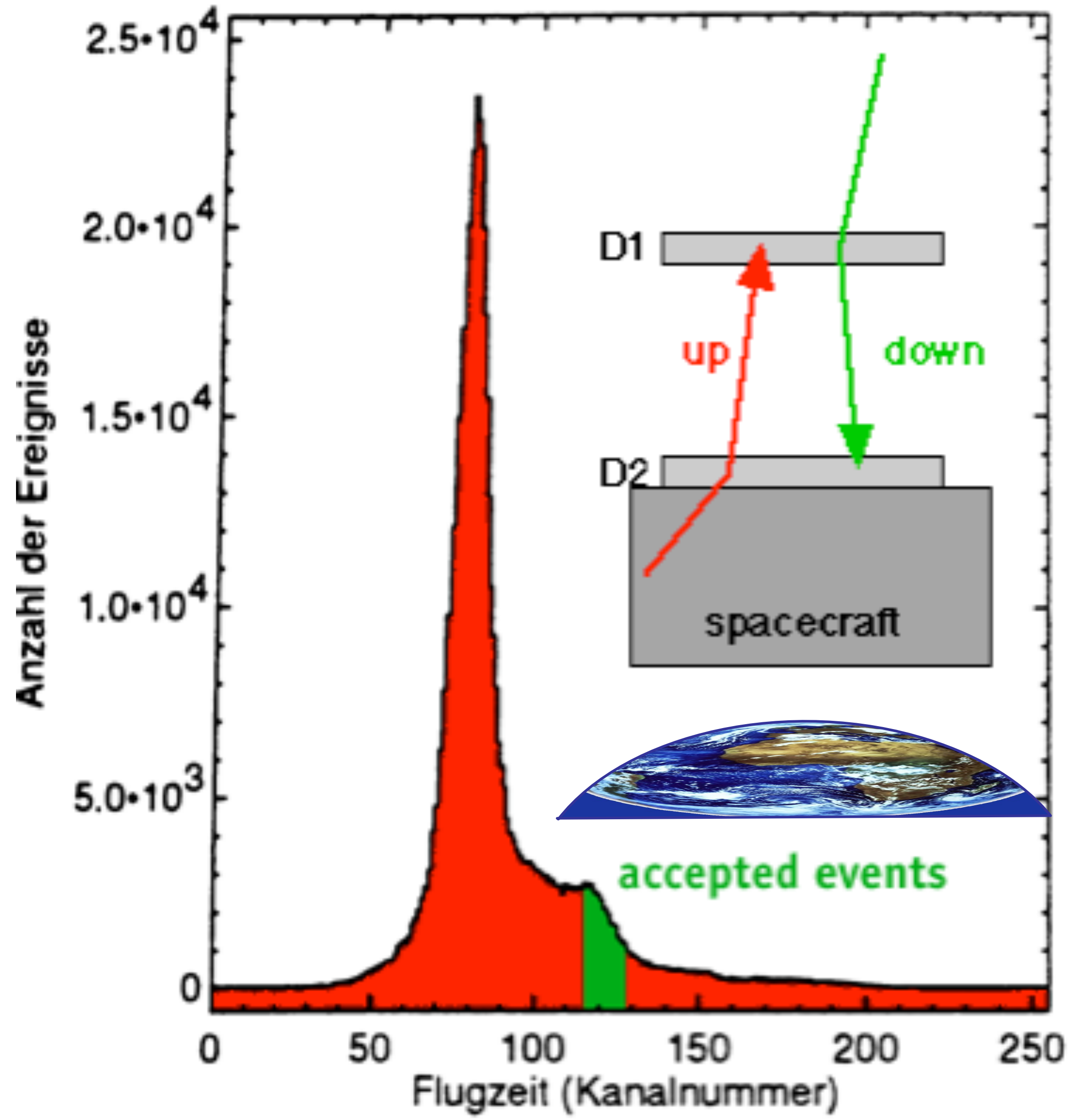


Compact solid state CTs

from von Ballmoos, Nov 2013, Instrumental Perspectives …

option B : anticoincidence shield





Compact solid state CTs
Higher Compton efficiency

from von Ballmoos, Nov 2013, Instrumental Perspectives …

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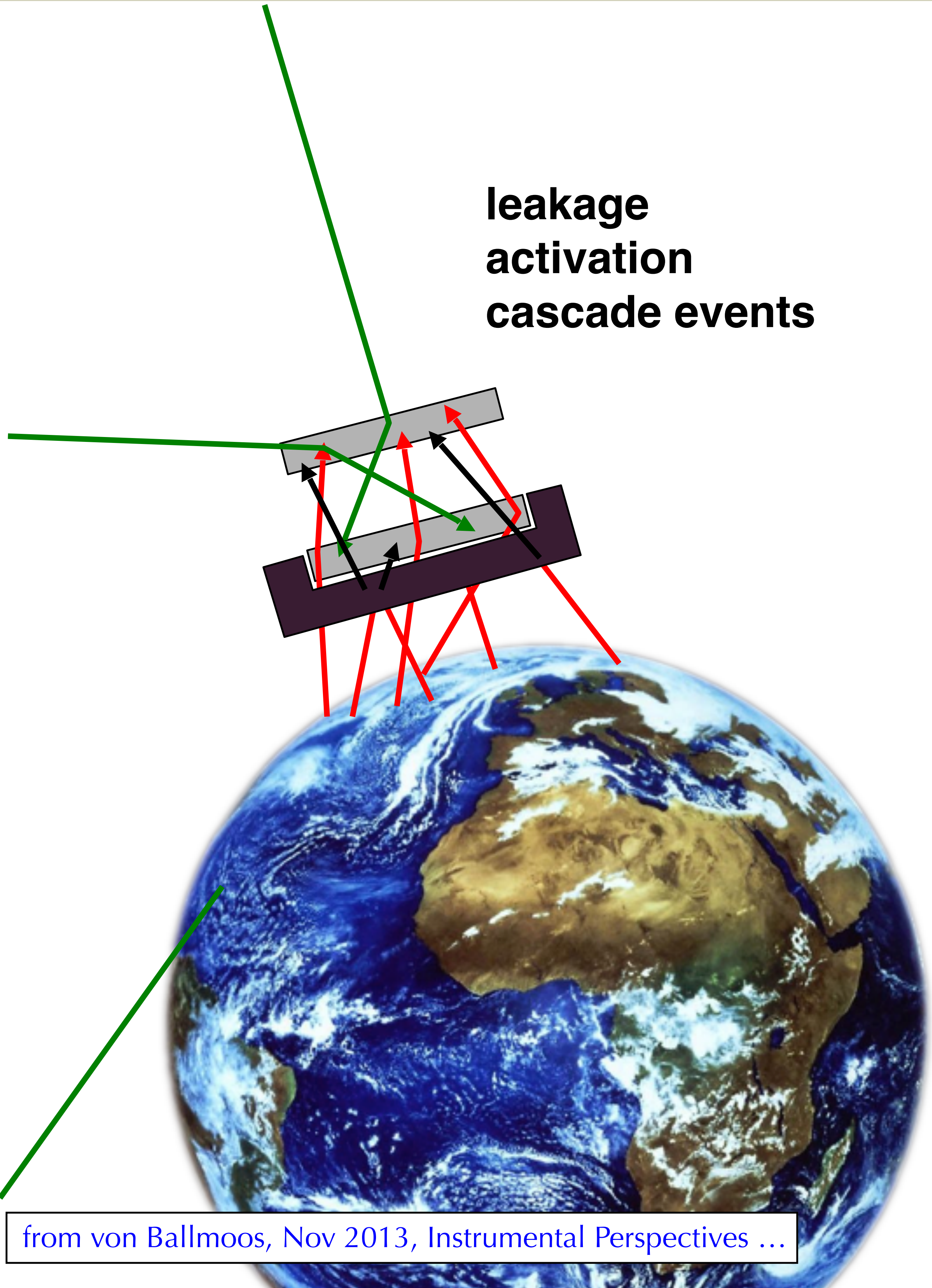
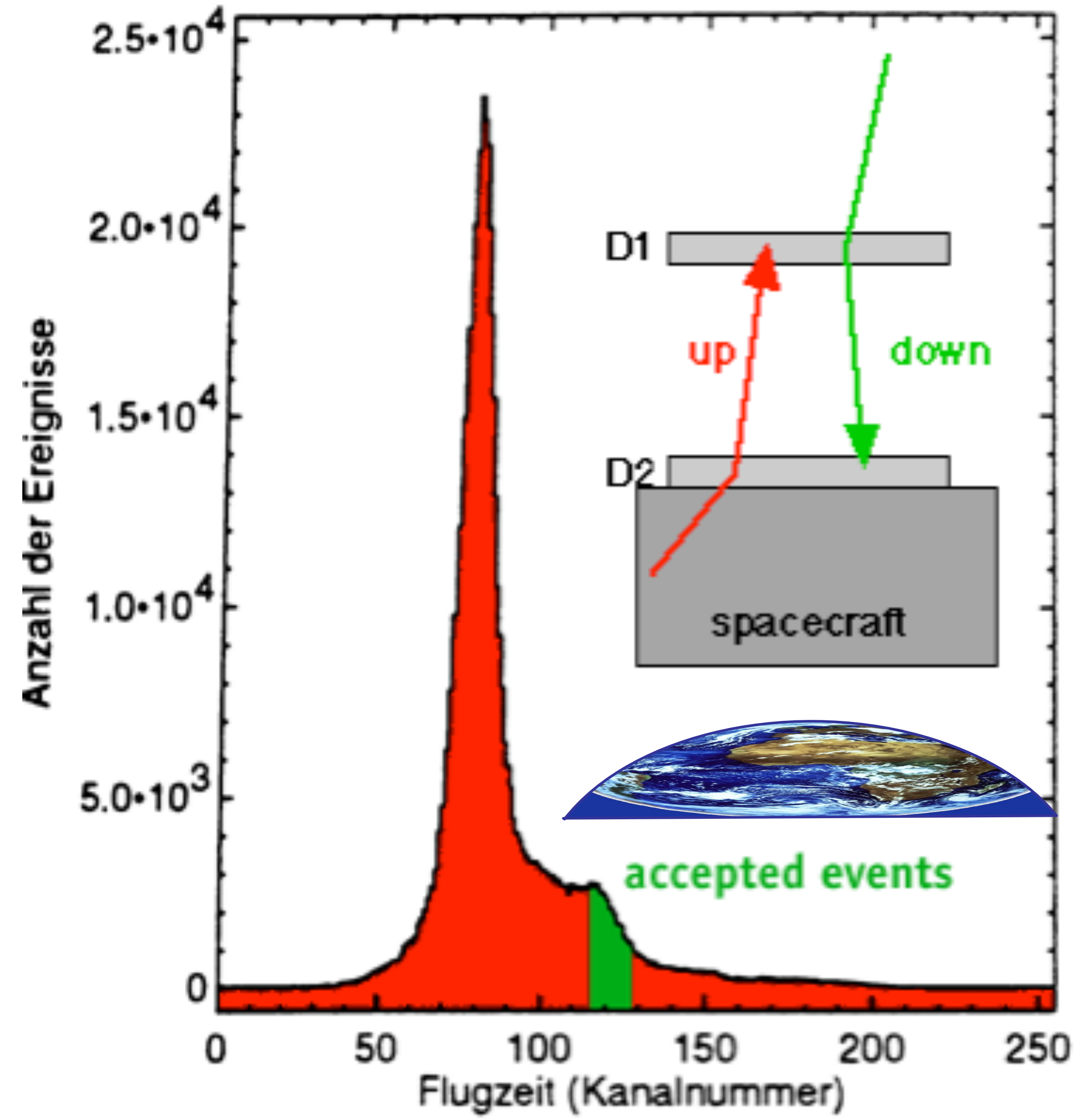




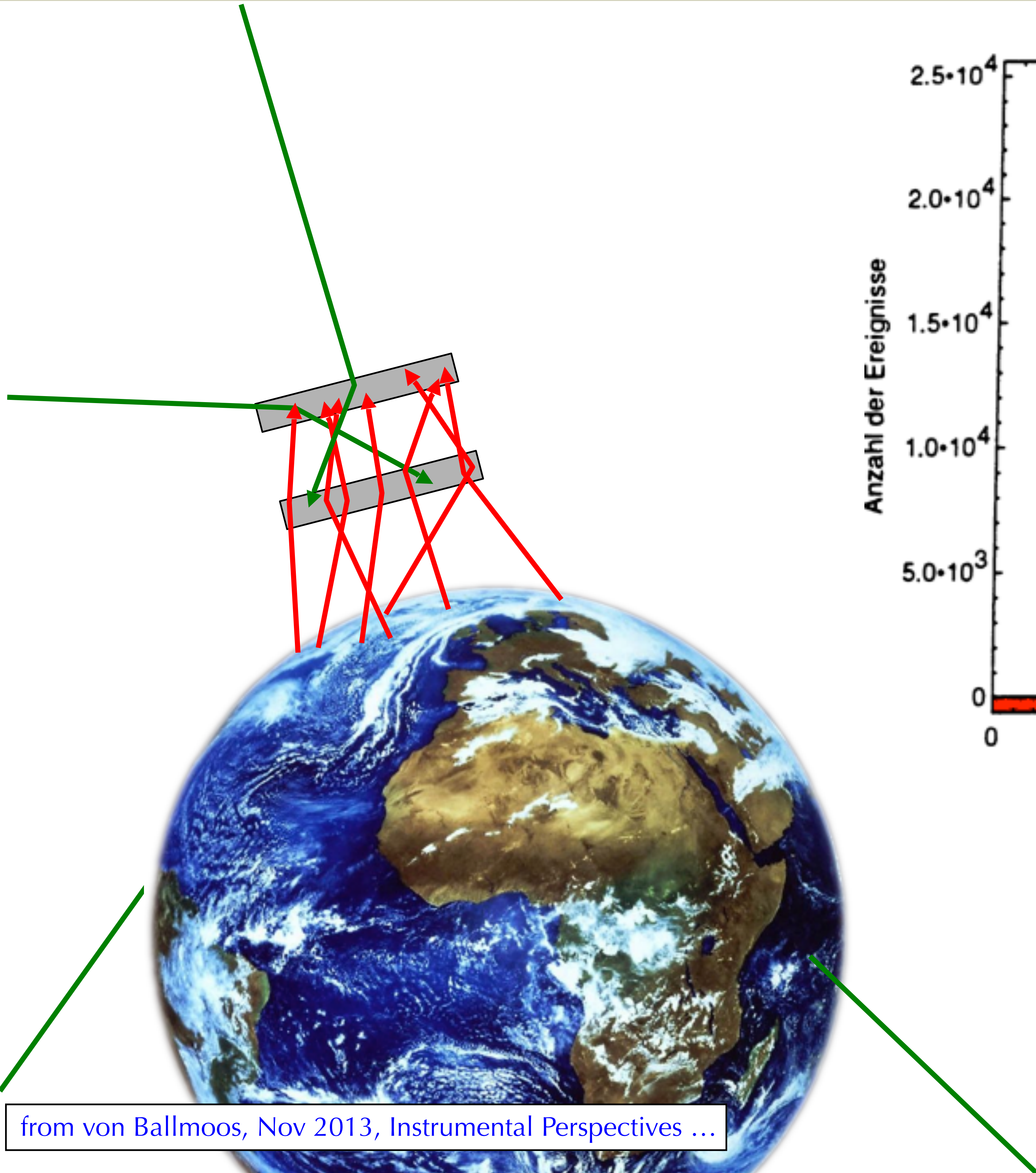
Compact solid state CTs

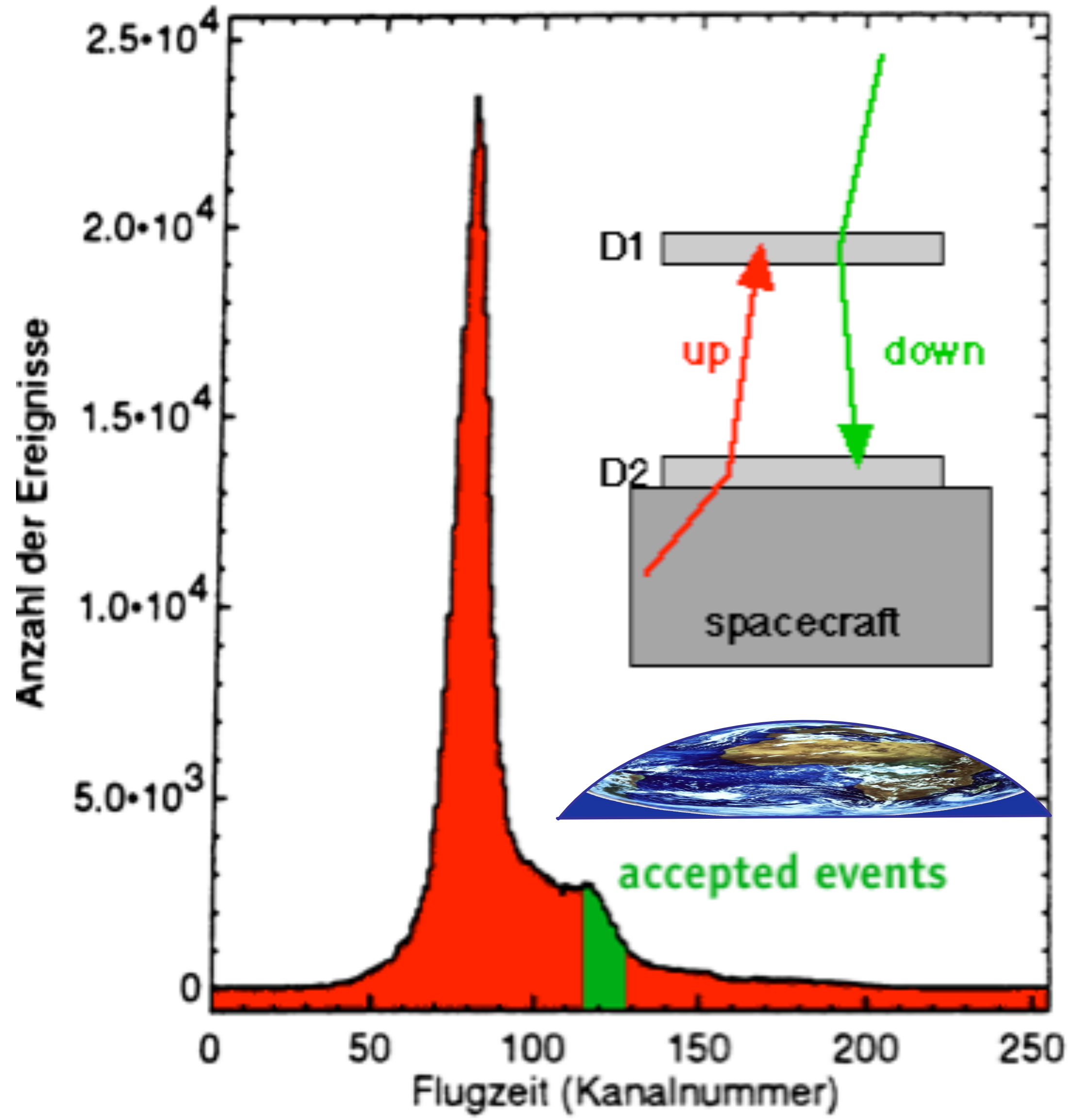
Higher Compton efficiency

They require **AC shields** often **more massive than the instrument** itself

from von Ballmoos, Nov 2013, Instrumental Perspectives …

option C : no bkg from external passive mass





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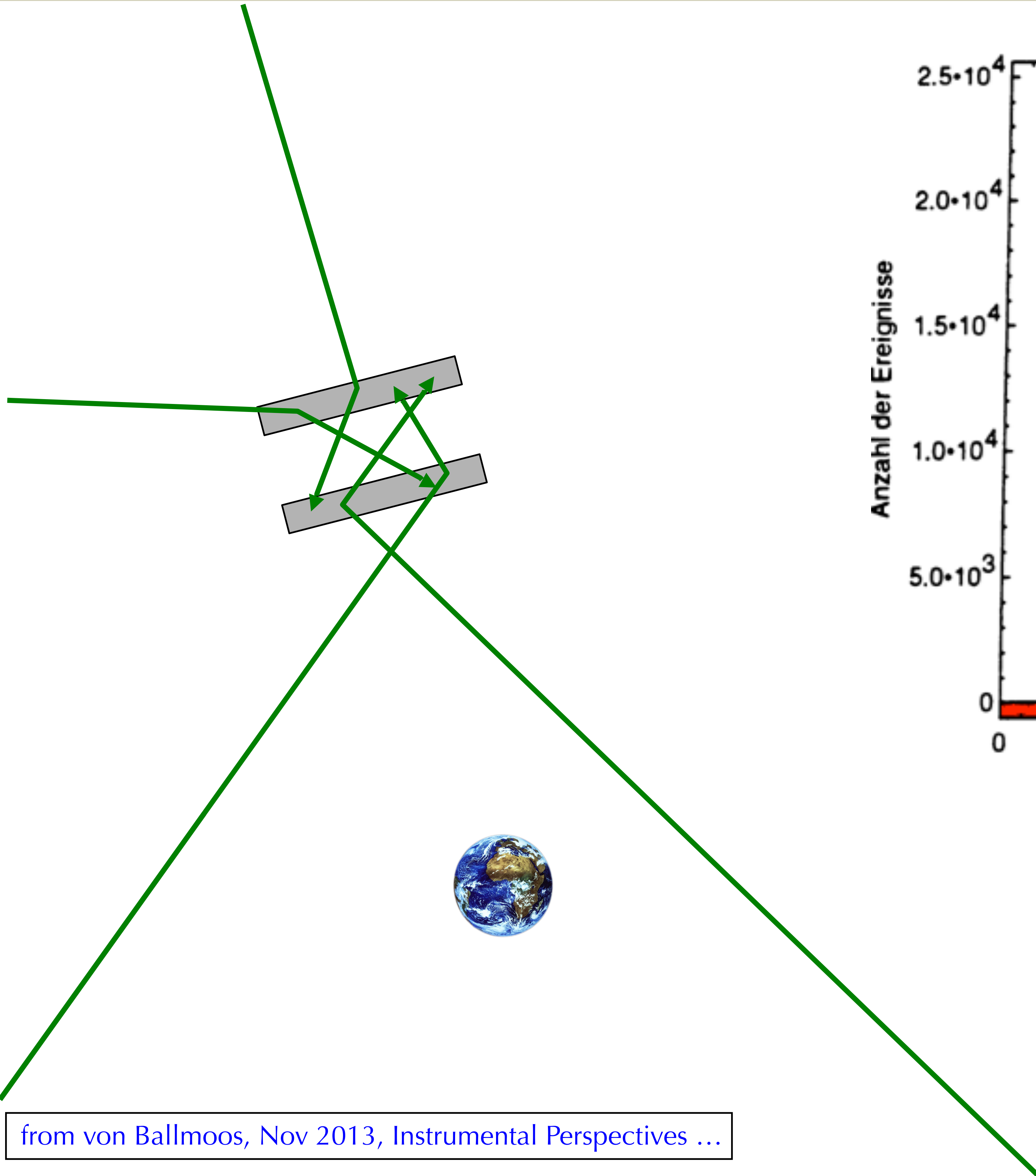

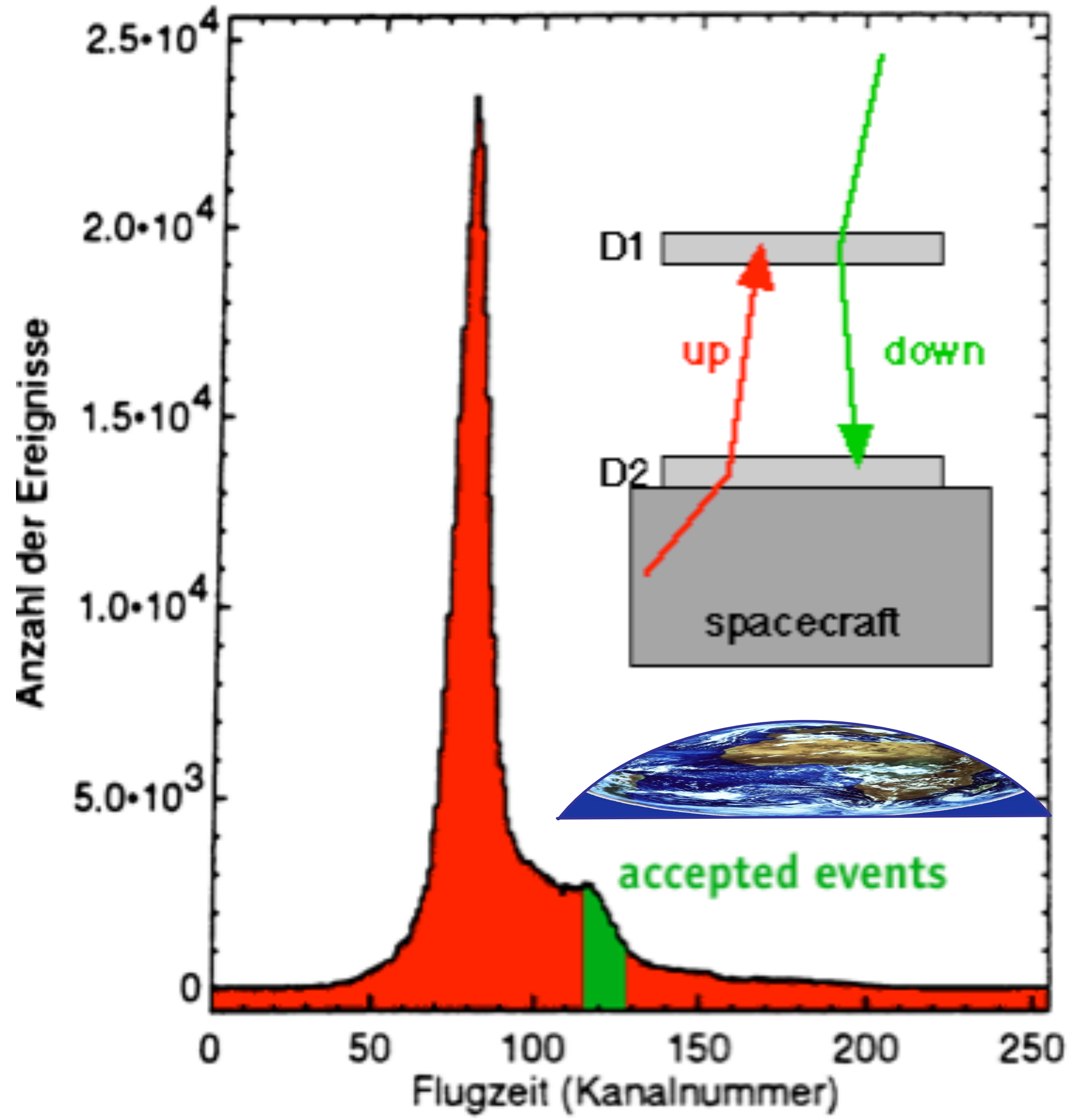

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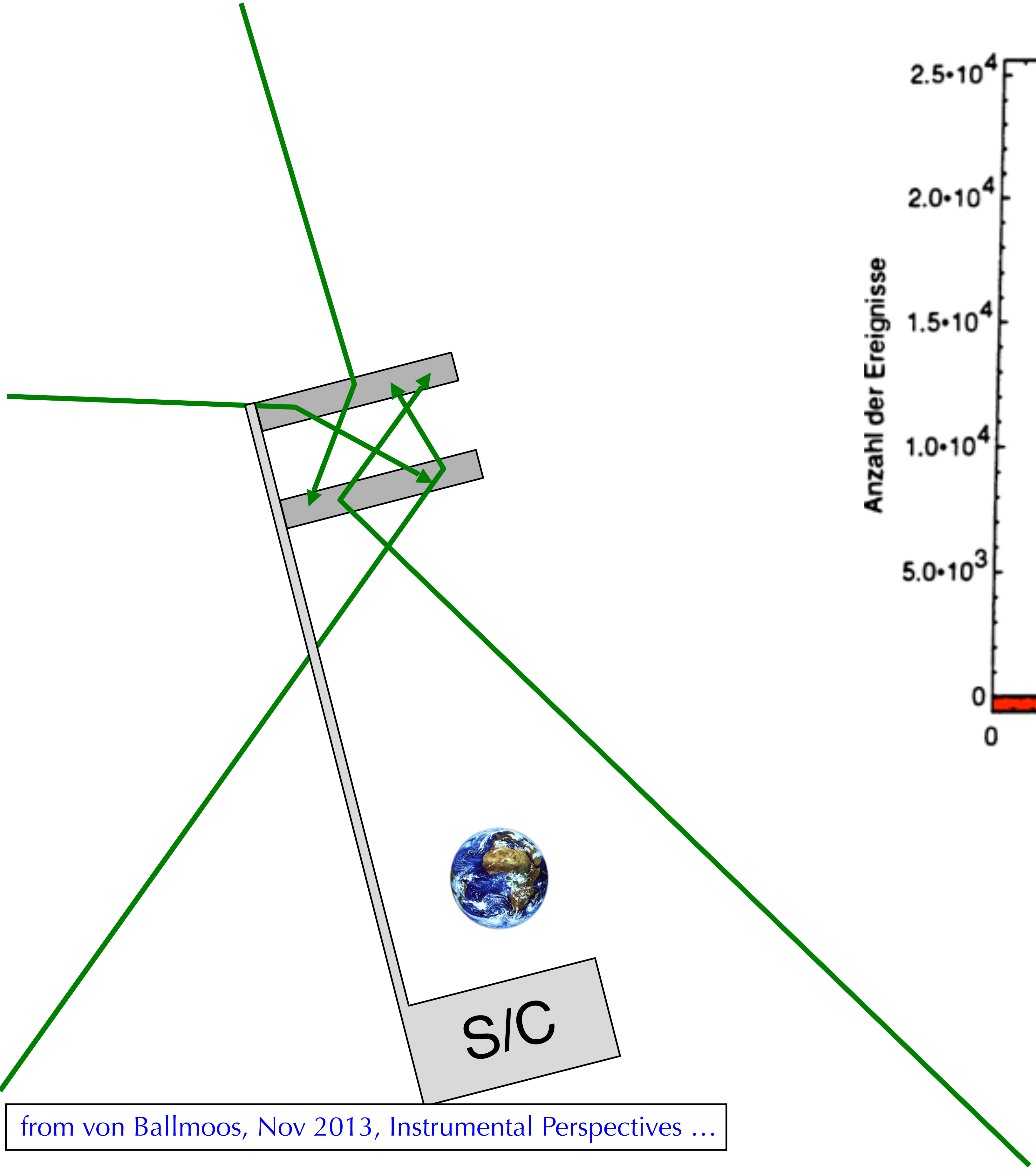

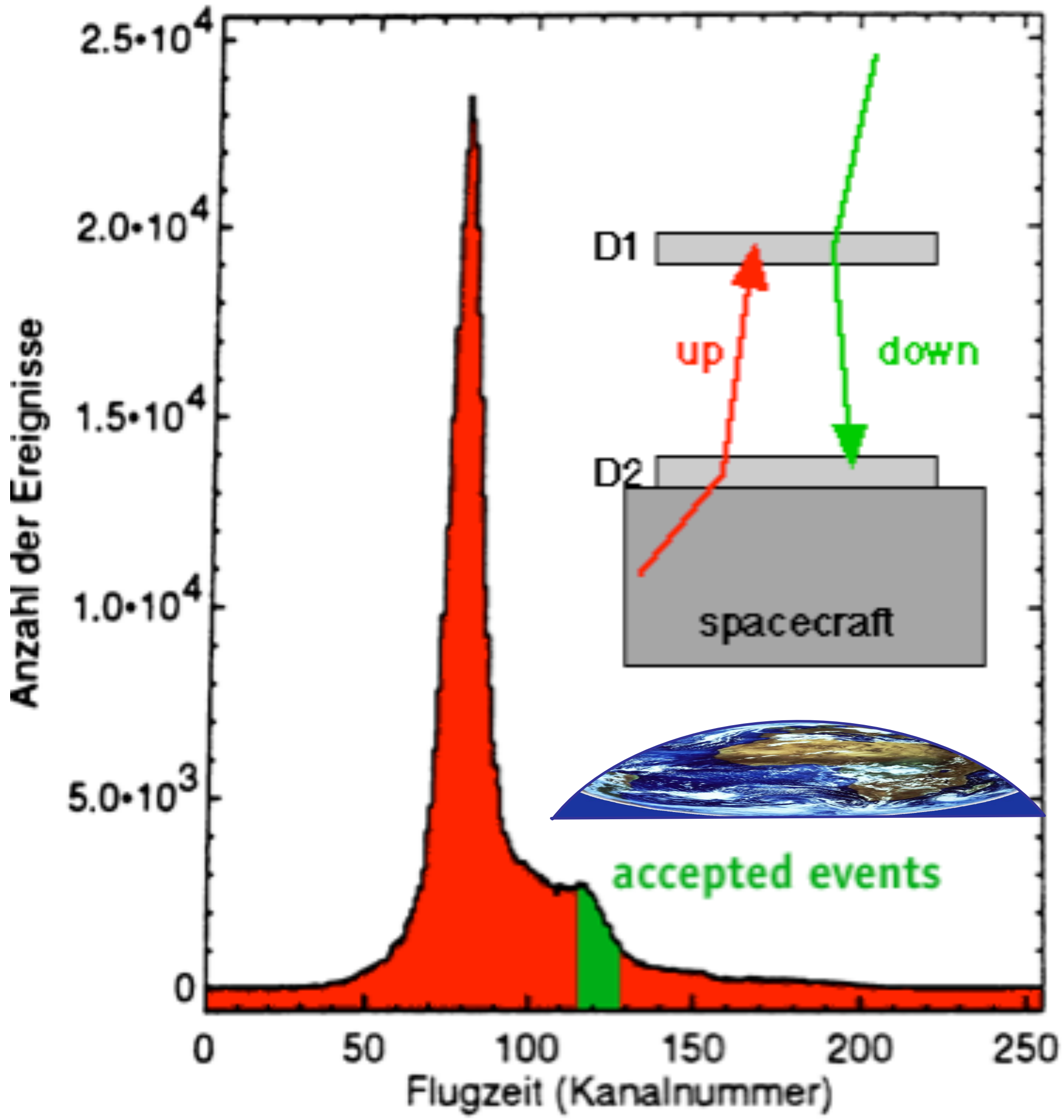

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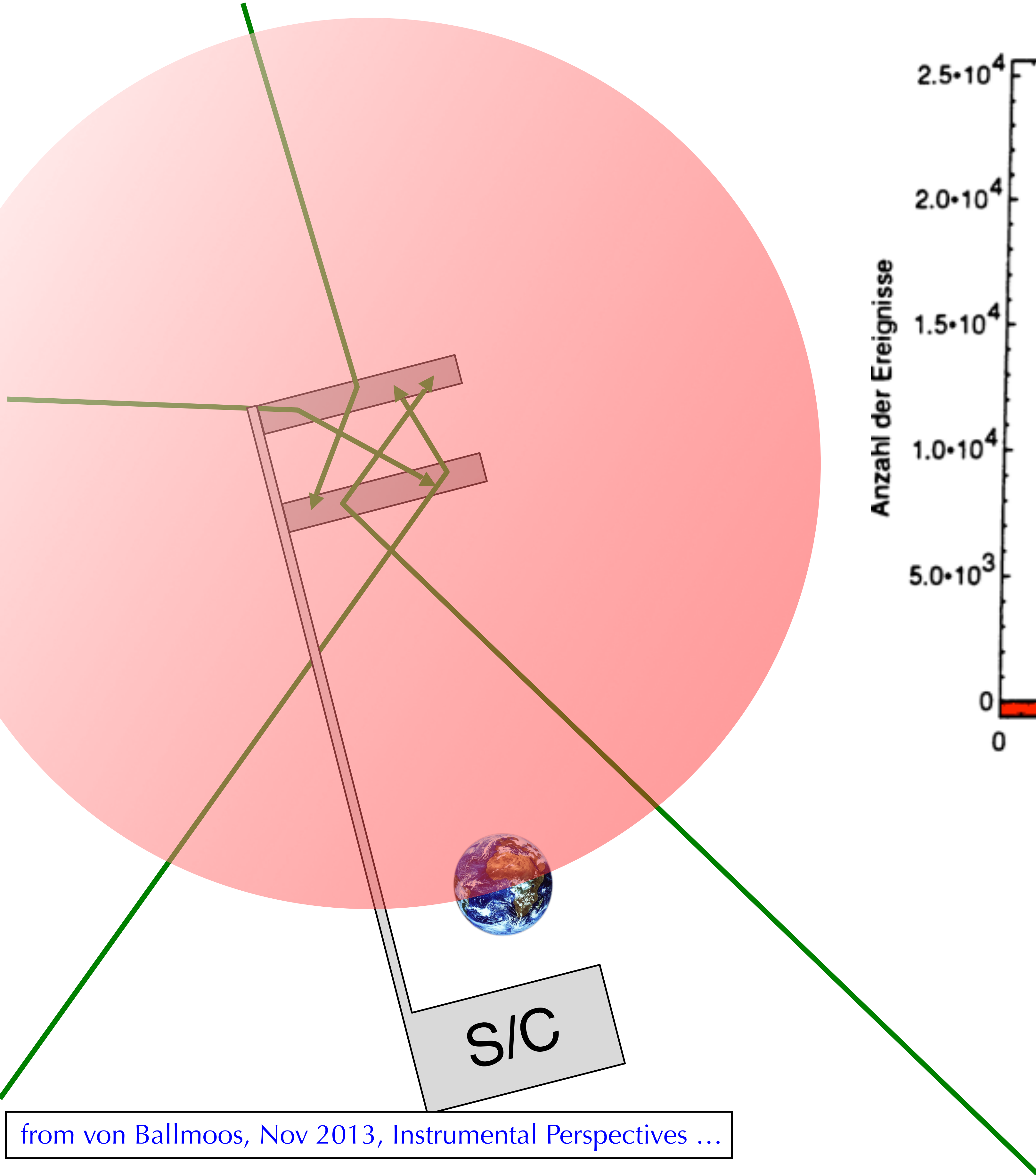
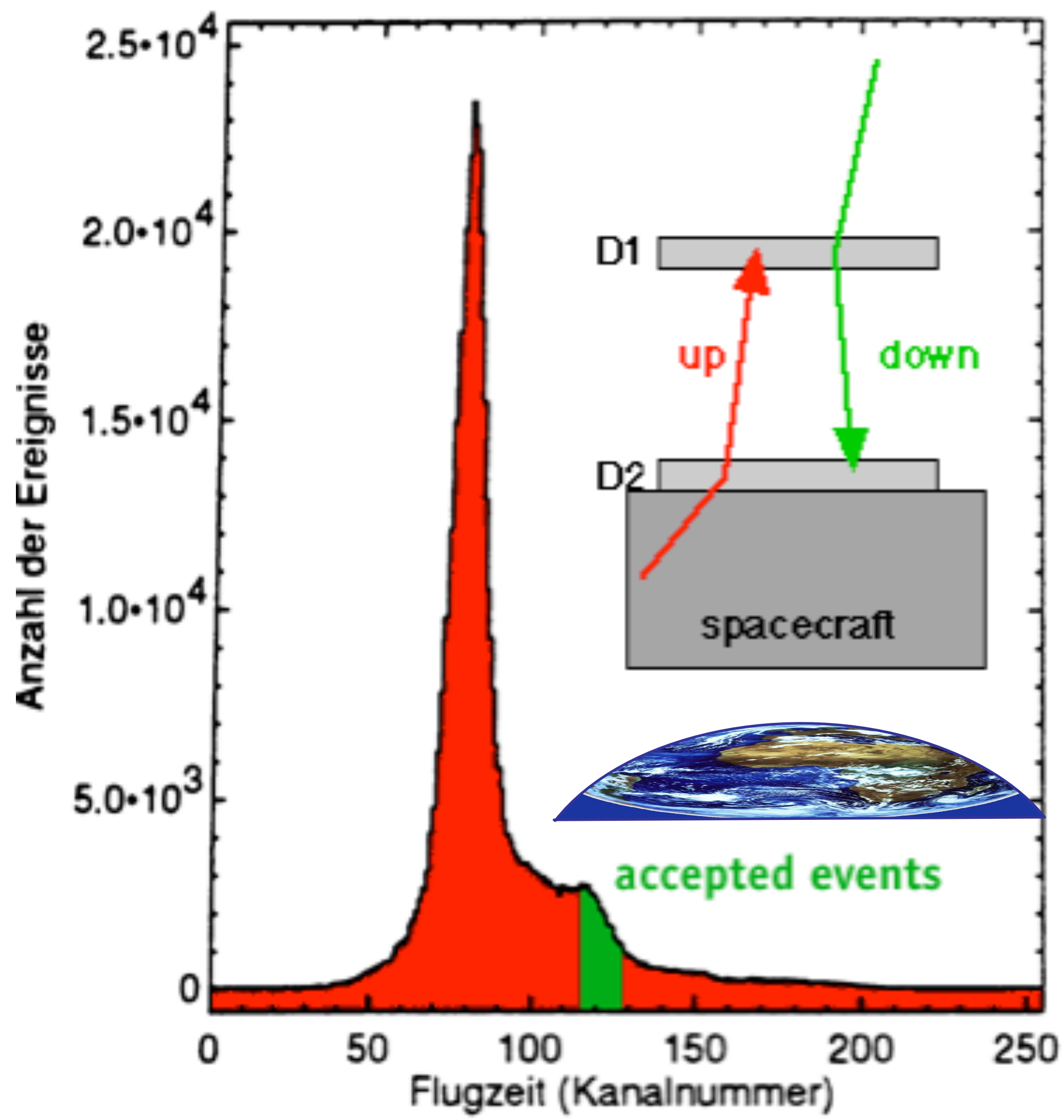


from von Ballmoos, Nov 2013, Instrumental Perspectives …

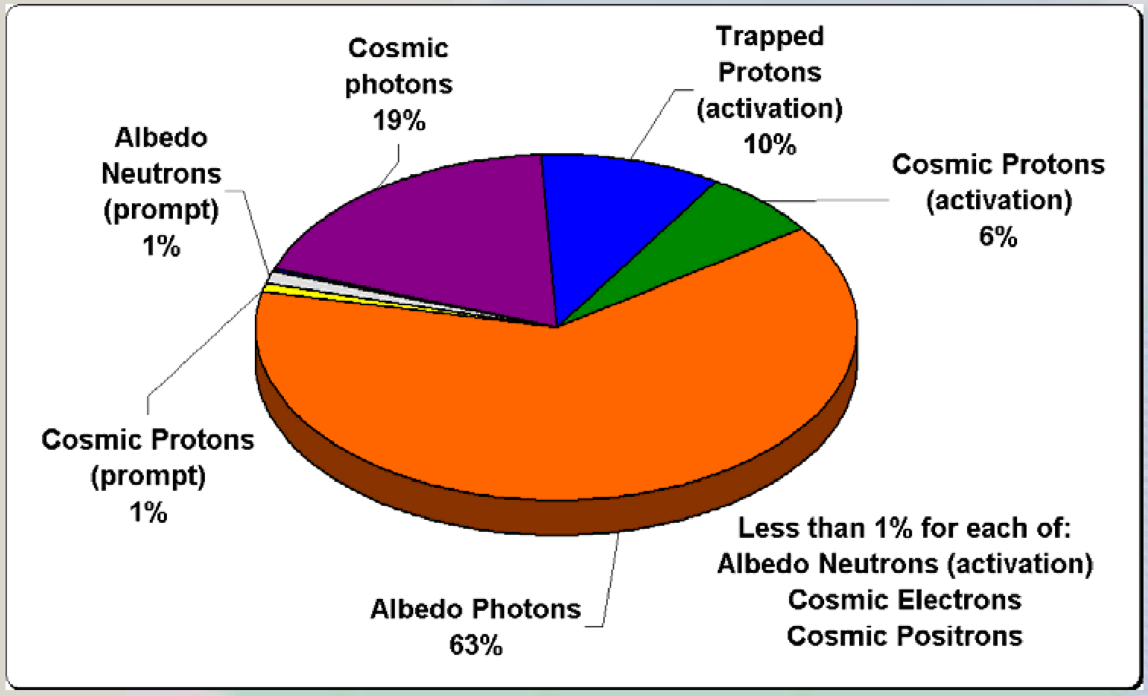


Which orbit? LEO or HEO?

- Low Earth Orbit
  - Advantages
    - Reduced CR background from geomagnetic shielding
      - Reduced prompt CR contamination
      - Reduced instrument and s/c activation
      - Note: want low inclination (i.e. near 0 deg)
        - » Maximizes geomagnetic screening, i.e. minimizes CR-induced bkg
        - » Improves livetime by avoiding SAA
    - Increased payload mass at lower launch cost
  - Disadvantages
    - Strong atmospheric g-ray background
    - Earth occults ~1/3 of the sky
- High Earth Orbit
  - Advantages
    - Reduced atmospheric g-ray background
    - Increased FOV (nearly 4pi possible)
  - Disadvantages
    - Increased CR background
      - Increased prompt CR contamination
      - Increased instrument and s/c activation
    - Decreased payload mass and/or higher launch cost

Example trade study for Si ACT

Low Earth Orbit vs. High Earth Orbit Background

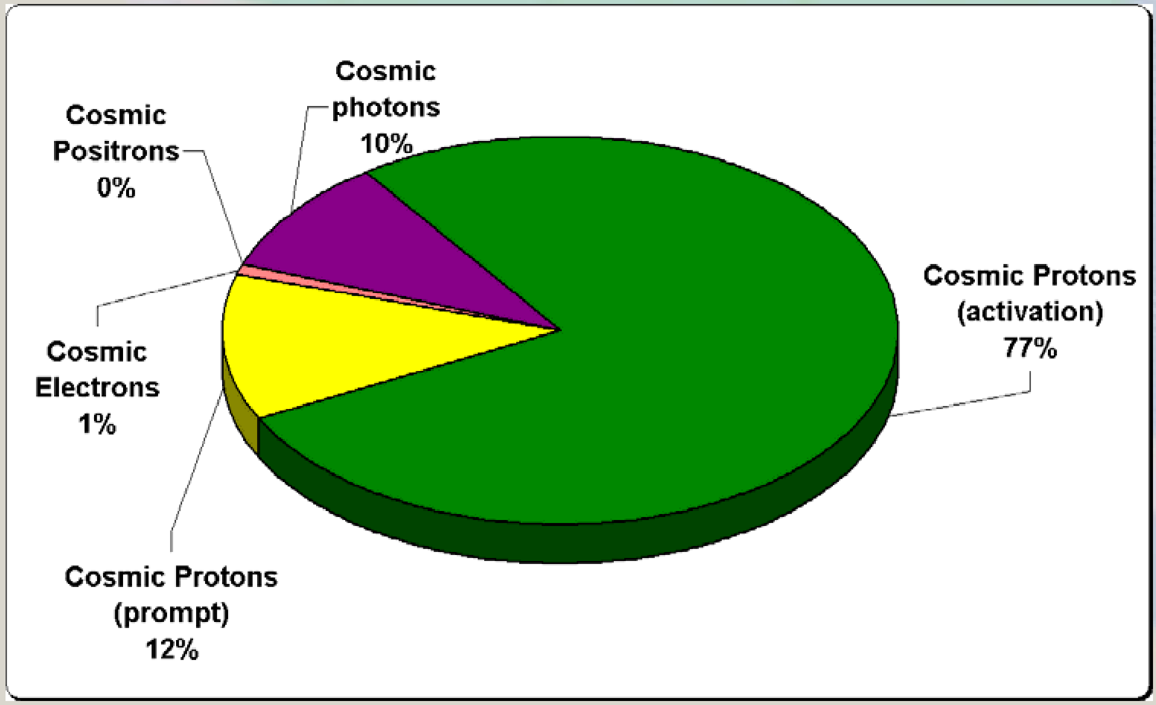


LEO: 550 km, 8^0 inclination

Contributions for: Horizon cut 92.5^0, E = 847 +/- 22.75 keV, ARM radius 1^0

3σ sensitivity over 10^6 sec, at 3% FWHM brdn. 847keV line, on-axis plain wave:

$2.37*10^{-6}$ $\gamma*cm^{-2}*s^{-1}$



HEO: 40,000 km

Contributions for: Horizon cut 10^0, E = 847 +/- 22.75 keV, ARM radius 1^0

3σ sensitivity over 10^6 sec, at 3% FWHM brdn. 847keV line, on-axis plain wave:

$2.97*10^{-6}$ $\gamma*cm^{-2}*s^{-1}$

Novikova (NRL) et al. 2005 – Si ACT

Backgrounds

- Beware of self-activity
  - Are lanthanum halides good choices for Compton calorimeter?
  - LaBr3, LaCl3
    - Fast scintillator, good energy resolution (~4% at 1 MeV), high stopping power
    - Hot (natural radioactivity)
  - Study performed for ACT, GRIPS

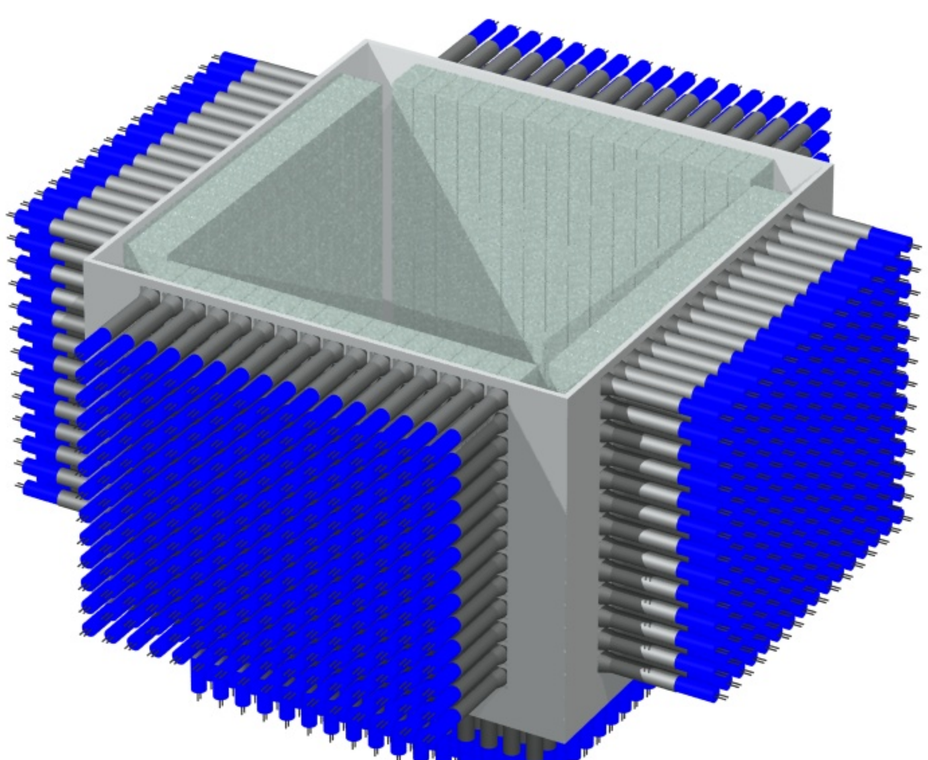
NaI vs LaBr Compton Calorimeter

Bernard Phlips

Code 7654

search Laboratory

Calorimeter



- NaI crystals are standard parts
- Frame will also support stack of silicon
- Need slots for cables from/to silicon detectors
- Area inside calorimeter ~ 45 cm x 45 cm

Note size

Self activity or induced activation

- Beta-gamma decays look just like signal
  - e.g. La self-activity for large instrument creates many kHz of nasty bkg

Lanthanum Activation

- Lanthanum is 99.91% ^{139}La, and 0.09% ^{138}La
- ^{138}La decays with 2 different decay schemes:- 788.7 keV gamma
  - 1438.8 keV gamma and a beta with 205 keV endpoint
- The activity is 1.8 Bq/cm^3 for $LaCl_3$ and 1.62 Bq/cm^3 for $LaBr_3$
- For 5 cm thickness, have ~30 000 cm^3 calorimeter.
- ~50 000 Bq of activity within the instrument for LaBr3!

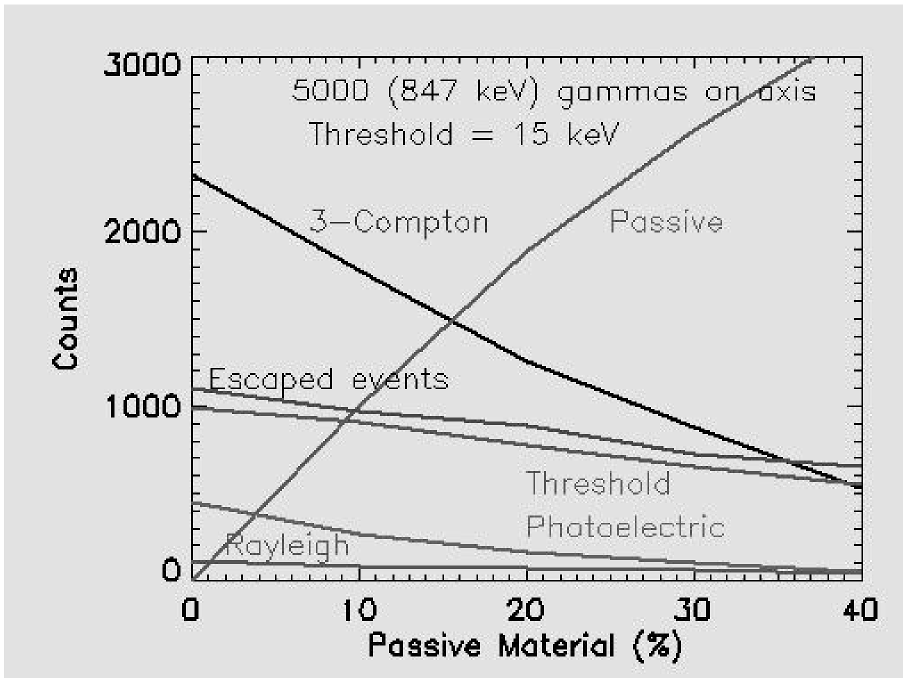
Hits in scintillator	Hits in Silicon: 0	1	2	3	4	5	6	7	8
0	16187	331	114	38	18	8	3	1	0
1	27814	782	324	124	43	10	5	1	1
2	22573	911	303	107	30	6	1	0	0
3	9801	462	124	27	6	3	0	0	0
4	2500	118	24	8	1	0	0	0	0
5	442	21	4	1	0	0	0	0	0
6	53	4	1	0	0	0	0	0	0
7	5	1	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	0

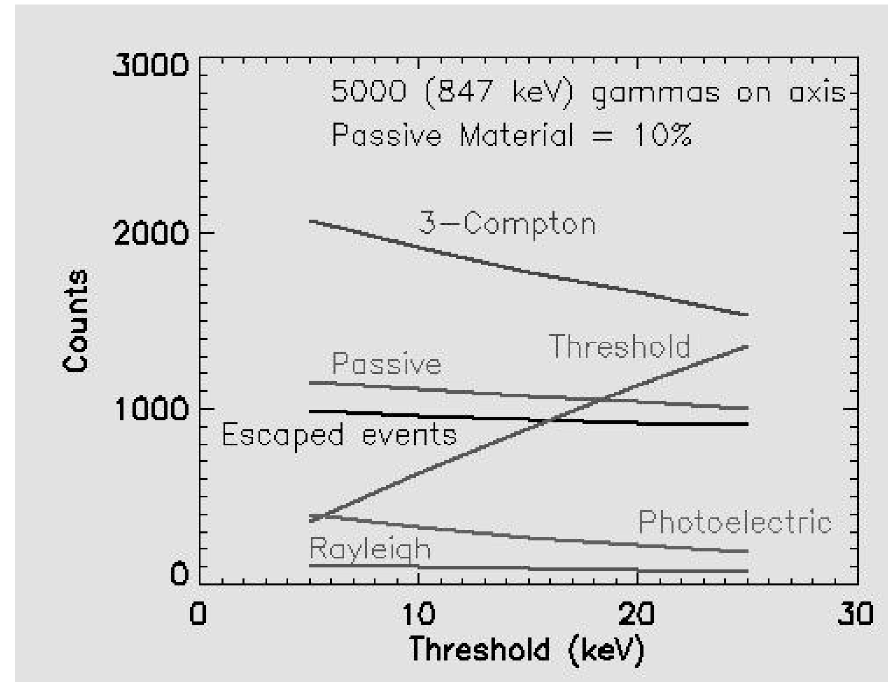
- We modeled the activity and logged the different types of events
- There are ~3500 coincidences/second between silicon and calorimeter from self activity!
- Lanthanum halides probably not the way to go for large instruments

from Phlips (NRL), 2005, NaI v. LaBr …

Passive material is bad

Sensitivity Improvement with New Technologies





- Current simulations result in about 2-4% effective area
- This is ≤ 10% of the potential events that could be used
- Clearly worth effort to substantially improve this performance

Reduce passive material

Reduce thresholds

from Phlips (NRL), 2005, NaI v. LaBr …

18 August 2005 ACT Team Meeting

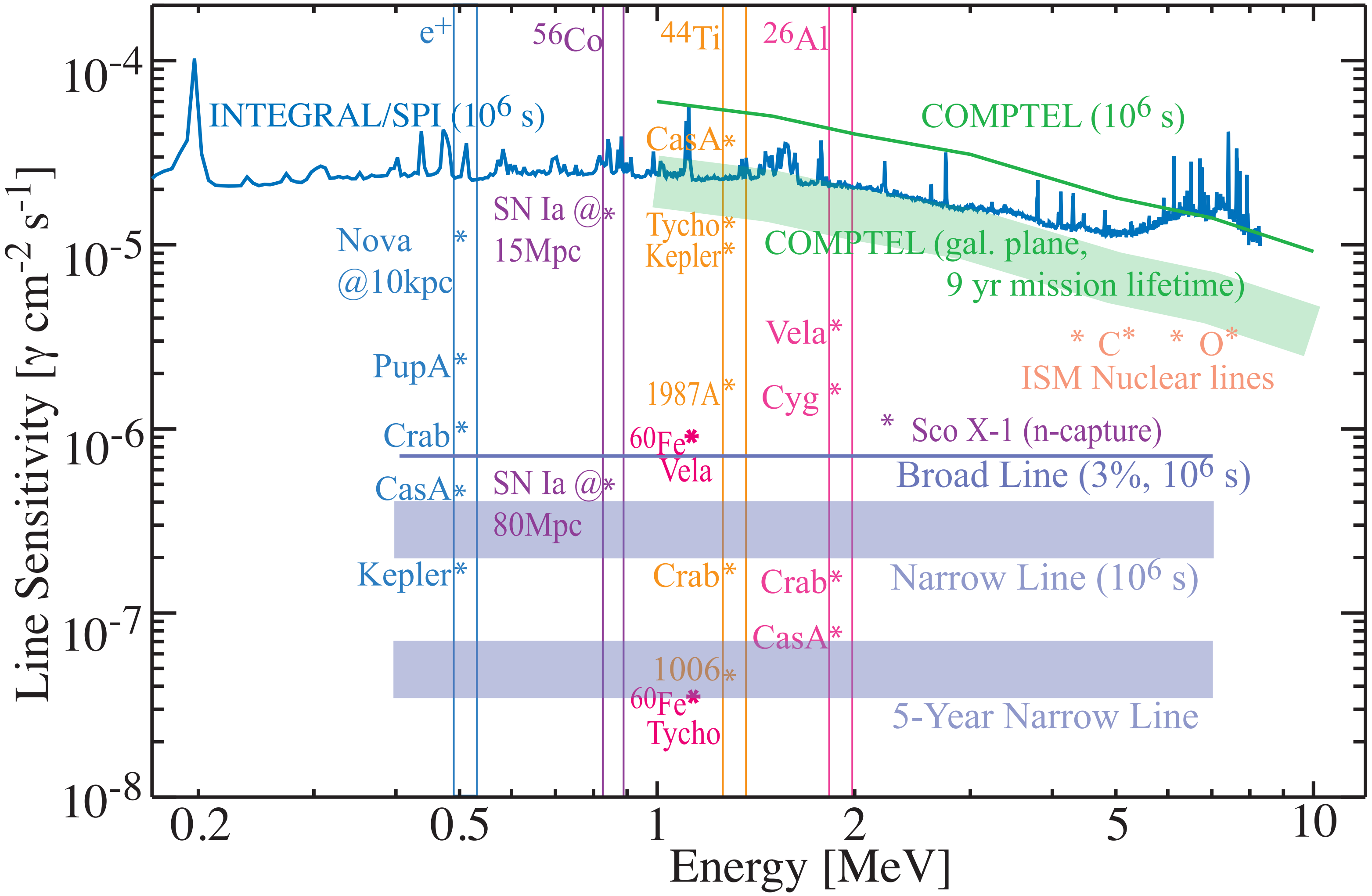
- Recall TKR passive material
  - Even after deleting W, trays are ~50% Si and ~50% passive Al-composite
    - Don't forget also that not all of Si is active

Desirements for high-res Compton tele

- Low Z scatterer
  - Minimizes Doppler broadening
  - Minimizes MCS of recoil electron, if tracking
- High Z absorber
  - Good stopping power to absorb scattered gamma (and minimize multi-Compton)
- High efficiency
  - Proper scatterer and absorber to give highest possible efficiency
  - Compact (as possible) to maximize geometric cross section for interaction
- Excellent energy resolution
  - Well matched with d^3x
- Fine position resolution
  - Well matched with dE
    - Thumb: ~1 mm and ~1 keV are commensurate
- Low-power electronics
  - Preserve intrinsic dE, d^3x of detectors while staying within power budget
- Minimal passive mass within detection volume
  - Interactions can be missed in passive material, and kill Compton performance
  - Minimize structural supports, co-located electronics

Performance goals

- If science is >10 MeV continuum
  - Sensitivity
  - PSF



- If science is <10 MeV lines and continuum
  - Continuum sensitivity
  - PSF
  - Narrow and broad line sensitivity
    - from Advanced Compton Telescope mission concept